

Institutionen för systemteknik

Department of Electrical Engineering

Examensarbete

Pilot Study of Systems to Drive Autonomous Vehicles on Test Tracks

Examensarbete i Reglerteknik utfört
vid Tekniska högskolan i Linköping
av

Erik Agardt
Markus Löfgren

LITH-ISY-EX--08/4042--SE

Linköping 2008



Linköpings universitet
TEKNISKA HÖGSKOLAN

Pilot Study of Systems to Drive Autonomous Vehicles on Test Tracks

Examensarbete i Reglerteknik utfört
vid Tekniska högskolan i Linköping
av

Erik Agardt
Markus Löfgren

LITH-ISY-EX--08/4042--SE

Handledare: **Christian Lundquist**
isy, Linköpings universitet
Göran Åhling
EDAC/Volvo 3P
Göran Åhlin
Volvo 3P

Examinator: **Thomas Schön**
isy, Linköpings universitet

Linköping, 28 March, 2008

	Avdelning, Institution Division, Department Division of Automatic Control Department of Electrical Engineering Linköpings universitet SE-581 83 Linköping, Sweden	Datum Date 2008-03-28				
Språk Language ☐ Svenska/Swedish ☒ Engelska/English ☐ _____	Rapporttyp Report category ☐ Licentiatavhandling ☒ Examensarbete ☐ C-uppsats ☐ D-uppsats ☐ Övrig rapport ☐ _____	ISBN _____ ISRN LITH-isy-ex--08/4042--SE Serietitel och serienummer ISSN Title of series, numbering _____				
URL för elektronisk version http://www.control.isy.liu.se http://www.ep.liu.se						
<table border="0"> <tr> <td style="vertical-align: top;">Titel Title</td> <td>Förstudie av System för Körning av Autonoma Fordon på Provbano Pilot Study of Systems to Drive Autonomous Vehicles on Test Tracks</td> </tr> <tr> <td style="vertical-align: top;">Författare Author</td> <td>Erik Agardt, Markus Löfgren</td> </tr> </table>			Titel Title	Förstudie av System för Körning av Autonoma Fordon på Provbano Pilot Study of Systems to Drive Autonomous Vehicles on Test Tracks	Författare Author	Erik Agardt, Markus Löfgren
Titel Title	Förstudie av System för Körning av Autonoma Fordon på Provbano Pilot Study of Systems to Drive Autonomous Vehicles on Test Tracks					
Författare Author	Erik Agardt, Markus Löfgren					
Sammanfattning Abstract This Master's thesis is a pilot study that investigates different systems to drive autonomous and non-autonomous vehicles simultaneously on test tracks. The thesis includes studies of communication, positioning, collision avoidance, and techniques for surveillance of vehicles which are suitable for implementation. The investigation results in a suggested system outline. Differential GPS combined with laser scanner vision is used for vehicle state estimation (position, heading, velocity, etc.). The state information is transmitted with IEEE 802.11 to all surrounding vehicles and surveillance center. With this information a Kalman prediction of the future position for all vehicles can be estimated and used for collision avoidance.						
Nyckelord Keywords Autonomous vehicles, GPS, DGPS, WLAN, fast handover, IEEE 802.11, laser scanner, lidar, collision avoidance, Kalman filter						

Abstract

This Master's thesis is a pilot study that investigates different systems to drive autonomous and non-autonomous vehicles simultaneously on test tracks. The thesis includes studies of communication, positioning, collision avoidance, and techniques for surveillance of vehicles which are suitable for implementation. The investigation results in a suggested system outline.

Differential GPS combined with laser scanner vision is used for vehicle state estimation (position, heading, velocity, etc.). The state information is transmitted with IEEE 802.11 to all surrounding vehicles and surveillance center. With this information a Kalman prediction of the future position for all vehicles can be estimated and used for collision avoidance.

Acknowledgments

We would first of all thank our supervisors at AB Volvo, Göran Åhlin and Göran Åhling. These two persons have been of great importance for the performance of this master thesis and have always encouraged and helped us during the time.

We would also thank Per-Olov Fryk who initiated this project, our examiner Thomas Schön, and our supervisor at the university, Christian Lundquist.

Finally we would thank all of the employees at Volvo 3P who have helped us and made our work a great time.

Erik Agardt and Markus Löfgren
Göteborg, January 2008

Contents

1	Introduction	1
1.1	Background	1
1.2	Volvo 3P	1
1.3	Problem Specification	1
1.4	Limitations	3
1.5	Thesis Outline	3
2	Position System	5
2.1	Satellite Navigation	5
2.1.1	Global Positioning System	5
2.1.2	Differential GPS	6
2.1.3	Carrier-Phase, L1\L2	8
2.2	Inertial Navigation System	8
2.3	Combined DGPS/INS System	8
2.4	Vision System	9
2.4.1	Line Following Systems	11
2.4.2	Camera Systems	11
2.4.3	Radar Sensors	11
2.4.4	Laserscanners	12
2.5	Complete Position System	17
3	Communication Systems	19
3.1	STDMA	19
3.1.1	VDL Mode 4	19
3.1.2	TACSYS/CAPTS	20
3.1.3	STDMA Summary	20
3.2	Wireless Local Area Network	20
3.2.1	IEEE 802.11	20
3.2.2	WLAN With Dual Antennas	21
3.2.3	Selective Channel Scanning	22
3.2.4	Handover Using Neighbour Graph	22
3.2.5	IEEE 802.11 Summary	25
3.2.6	ZigBee	25
3.2.7	WiMax	26

4	Collision Avoidance	27
4.1	Collision Avoidance Prediction	28
4.2	Vehicle States Message	37
4.3	Collision Avoidance Vision	38
5	Measurements and Data Collection	41
5.1	GPS coverage	41
5.1.1	Static GPS Coverage Hällered	41
5.1.2	Test Track GPS Coverage	42
5.1.3	GPS Accuracy	44
5.1.4	Dual GPS	48
5.1.5	Differential GPS	48
5.2	Laser Scanner Data Collection	53
5.3	WLAN coverage	54
5.3.1	WLAN range	54
6	Conclusions	57
6.1	Positioning Conclusions	57
6.1.1	Positioning	57
6.1.2	Vision	58
6.2	Communication Conclusions	58
6.2.1	WLAN	58
6.3	Surveillance Conclusions	59
6.4	Collision Avoidance Conclusions	59
6.5	System Movability Conclusions	59
6.6	Future Work	59
6.6.1	Positioning System	59
6.6.2	Lidar System	60
6.6.3	Communication System	60
6.6.4	Collision Avoidance System	60
6.6.5	Fault Detection	60
	Bibliography	61
A	Satellite Navigation	67
A.1	History	67
A.2	GPS	67
B	Inertial Navigation Systems	73
B.1	Dead Reckoning	73
C	Prototype Systems	76
C.1	PATH	76
C.2	VW Golf GTi 53 ⁺¹	76
C.3	Team LUX	77
C.4	Previous Volvo projects	77
C.4.1	LKAB	77

C.4.2	VTEC Prototype truck	77
D	Mathematics	79
D.1	Haversine Equation	79
D.2	Covariance	79
E	Kalman filter	80
E.1	Extended Kalman filter	80
F	Globalsat	82
G	Oxford Tech RT 3002	87
H	Oxford Tech RT-Base	90
I	Cisco Aironet 1240G Series Access Point	93
J	Antenna Specifications	100

Chapter 1

Introduction

1.1 Background

This master thesis has its background at Volvo's test track at H  llered. On the test track an endurance circuit is built with the purpose to expose the vehicles tested to general wear and tear. The drivers are exposed to very hard working conditions primarily because of heavy vibrations when driving repeatedly numbers of laps on the endurance track. Long time exposure to these conditions is not suitable for the human physique. The drivers' working environment would benefit from a decrease of the exposure to vibrations. In order to obtain as much measurement data as possible without causing the driver harm, the idea to investigate the possibility to drive vehicles autonomously. With an autonomous vehicle, it is possible to repeat the path on the track with a higher precision than a human driver can achieve. There were several questions to be answered, such as: Is this project possible? Which techniques should then be used? Which modifications should be done at H  llered? To answer these questions, Volvo initiated this as a master thesis project for two master students. The result is a pilot study that are investigating if the theory of autonomous driving is possible and if so an investigation of what kind of equipment would be needed to implement this idea.

1.2 Volvo 3P

This master thesis has been performed at Volvo 3P. Volvo 3P is a business unit within AB Volvo that works with Volvo Trucks, Mack Trucks, Renault Trucks and BA Asia. 3P stands for Product Planning, Purchasing, Product Development and Product Range Management for the companies within AB Volvo.

1.3 Problem Specification

The primary goal of this thesis work is to investigate the possibilities of autonomous operation of vehicles. The aim is to design a system allowing several au-

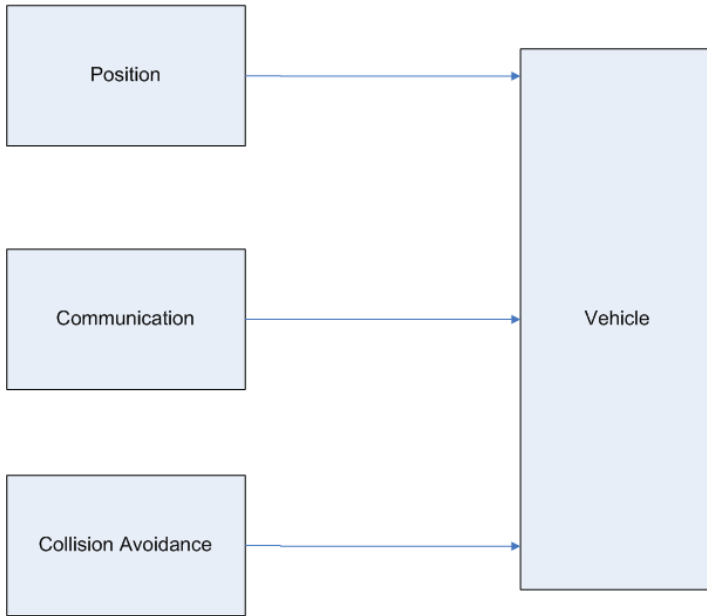


Figure 1.1. A proposed system structure. Three different subsystems supply the vehicle with information needed to run autonomously.

onomous and non-autonomous vehicles to use the test track simultaneously while maintaining adequate safety. Our task is to suggest techniques for implementations, which are suitable and cost efficient, for positioning, collision avoidance, communication, and surveillance of vehicles.

- The positioning performance of the system must be in the range of the width of the road.
- The collision avoidance system must be able to prevent collisions with other vehicles and obstacles.
- The communication performance must at least be able to send information of vehicle states¹ and receive information of other vehicles' states. The system's ability to transfer information in addition to vehicle status shall also be estimated.
- The surveillance must be able to monitor all active vehicles and their states.
- The complete system must be movable to other sites.

We will be studying three different structures which will handle the problem specification. See Figure 1.1.

¹Vehicle states include position, velocity and status of the vehicle

1.4 Limitations

In this thesis, the data collection is limited to Göteborg, Hälleröd, and nearby areas. For that reason the moveability and the system performance at other test tracks cannot be evaluated in this thesis. The hardware tested is limited to equipment available at AB Volvo. The system designed may consist of other parts, which have not been validated. This thesis will not include control of an autonomous vehicle.

1.5 Thesis Outline

In the following chapters we will investigate the different sub-systems and present the techniques for these.

Chapter 2 describes different navigation systems and navigation tools to be used in our application.

Chapter 3 compares the different communication techniques that have been investigated and describes the theoretical background.

Chapter 4 describes the principles and techniques which are used to prevent collisions between autonomous vehicles, non-autonomous vehicles, and other objects.

Chapter 5 presents the data that has been collected for this project.

Chapter 6 summarizes the thesis. This chapter also includes suggestions for future work to expand this project.

Chapter 2

Position System

To obtain a position of a vehicle several different techniques can be used. This chapter will introduce the techniques which have been investigated. The major problem of the positioning is the accuracy. The systems considered in this chapter are positioning by satellite navigation, vision units, and dead reckoning.

2.1 Satellite Navigation

Positioning by satellite navigation is nowadays a very common feature. The most used system is the NAVSTAR Global Positioning System (henceforth referred as GPS in this thesis).

2.1.1 Global Positioning System

The basic function of satellite navigation and GPS function is described in Appendix A. Many vehicles nowadays can have a GPS wayfinder integrated within the vehicle. This is often a typical commercially available GPS receiver¹ unit with an update frequency of 1 Hz and with a standard deviation accuracy² of 15 m. This accuracy is too low to fulfill the demands of keeping a vehicle within one lane of the road. To obtain the demands of the positioning system the standard deviation needs to be less than 1 m [1]. Even the update frequency of the position in a typical GPS is too low (see Example 2.1). A GPS unit with a higher update frequency and with a standard deviation accuracy of 15 m has an accuracy which is too imprecise. Our conclusion is that the typical GPS not qualifies to be a part of the positioning system.

¹The phrase *typical GPS receiver* is referring to the Garmin GPS 35/36 that is used as a standard component within Volvo trucks [1]

²The positioning standard deviation, 95% of the time

Example 2.1: 1 Hz GPS example

If the GPS update frequency is 1 Hz and the test vehicle is traveling at 15 m/s (54 km/h). The vehicle will advance 15 m between measurement positions. This can be a serious problem in for instance cornering manoeuvres. To obtain the wanted resolution (in meters) the GPS update frequency can be estimated by the following equation.

$$Frequency[Hz] = \frac{Velocity[m/s]}{Resolution[m]} \quad (2.1)$$

2.1.2 Differential GPS

A differential GPS is an enhancement to the standard GPS system. It operates by a stationary ground network or by fixed ground local stations. By knowing the exact position of the stationary receiver, it can calculate the errors from satellite signals and send out the differential corrections to the vehicle. A base station covers a small area and the differential correction is a local correction. There are several different techniques that are currently in use to obtain the differential correction signals. The two most common techniques are *Wide Area Correction System* (WACS) and *Local Area Correction System* (LACS) [48].

EGNOS/WAAS

European Geostationary Navigation Overlay Service (EGNOS) is a Satellite Based Augmentation System (SBAS) that is under development in Europe. The EGNOS system is a WACS. The system started operations in July 2005, and will be certified for use in 2008. The North American Wide Area Augmentation System (WAAS) is similar but has no European coverage [21]. EGNOS uses three geostationary satellites which send out a ranging signal (similar to ordinary GPS signal). EGNOS also uses a network of ground stations that calculates the errors (clock, ionospheric disturbances, etc.) and sends out a correction signal (see Figure 2.1). This correction increases the accuracy of the GPS to approximately 2 m [19]. The problem with this system is that the accuracy is not good enough to keep the vehicle within one lane of the roadway.

SwePos

The Swedish GPS correction service EPOS is available for use. The service is provided by the Swedish company SwePos. It uses the FM-radio frequency to send out the correction signals. The coverage of this technique is very good for use in Sweden but the update frequency is between between 3 and 5 seconds. The accuracy is good, but the update frequency is too slow [57]. For that reason this technique is not suitable for this project.

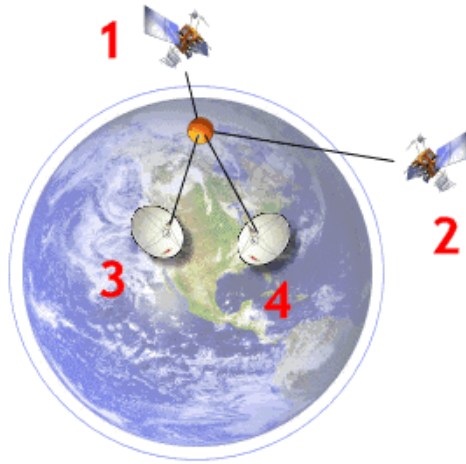


Figure 2.1. Wide Area Correction System (WACS). Two GPS satellites (1 and 2) with stationary reference stations (3 and 4) that supplies the user with position information and correction signals to obtain a high accuracy position [50].

SwePos also offers a Network Real-Time Kinematic correction. This is based on a subscription provided by the GSM network. This provides with centimeter accuracy but the correction service is expensive and every user needs a subscription [57]. This technique is not suitable to our demands due to the subscription cost.

OmniSTAR

The OmniSTAR is a GPS system which offers GPS correction which can improve the accuracy of the GPS receiver. The OmniSTAR concept is a subscription service to their GPS receiver. The subscription supplies the customer with access to the correction signal of their satellites. It works like a WACS system, where multiple OmniSTAR GPS reference sites calculate the error of the signal. By sending up correction signals to the satellites from the American and Australian Network Control Center the correction data is received and applied in real-time. The system is available with an accuracy below 10 cm with the OmniSTAR service subscription [45]. This technique provides great accuracy but is still dependent on a subscription service for every user and because of this service it is not suitable for this project.

Local Area DGPS

One option to get differential correction signals is to use a separate DGPS base station. The range of the base station is limited, and the position accuracy decreases with increasing distance to the base station. The base station is stationary and sends out correction signals to the DGPS receiver with e.g. a radio modem. With the local area correction signals the DGPS receiver obtains great accuracy. A position accuracy below 50 cm is achievable with this technique. The local area

DGPS system is fairly expensive to implement, but it is free from any subscription services and is very suitable for implementation within a restricted area. The cost of implementing a local DGPS system is according to given indications, in the same range as one single year of subscription fees for eight units using e.g. Omnistar services. The local DGPS system is not limited to a number of users and it offers a high grade of accuracy [48]. This technique is very suitable to our demands and will be further investigated.

2.1.3 Carrier-Phase, L1\L2

A typical GPS receiver calculates its position by the data that is sent from the GPS satellites. A second form of precise monitoring is called Carrier-Phase (CP) Enhancement. In order to obtain greater accuracy such a GPS receiver uses the CP from the satellite signal. The CP approach utilizes the L1 carrier wave³, which has a period a thousand times smaller than the bit period of the Coarse/Acquisition code (C/A), as an additional clock signal in order to reduce the uncertainty. The phase difference error in the normal GPS results in a position error within 2 to 3 meters. Using the CP method, this position error could, in the ideal case, reach 3 cm resolution⁴. Realistic use of a CP-GPS (L1) coupled with differential correction, Carrier Phase DGPS (CDGPS), gives a normal position accuracy of approximately 50 centimeters. If this technique is expanded with a L1\L2 receiver, the accuracy is at centimeter level (see appendix A.2). An accuracy comparison is presented in Figure 2.2 and Table 2.1 [48, 42]. To keep the vehicle within the roadway, a CDGPS would be recommended.

2.2 Inertial Navigation System

An inertial navigation system is a completely independent system⁵. The positioning is based on integration of the small changes in direction and velocity. This is detected by an Inertial Measurement Unit (IMU). Due to the minor offset in the change of the position, the new calculated position can quickly drift to a great error. See Figure 2.3 for a schematic drawing of an inertial navigator. This system is not suitable for use as a stand alone system due to the increasing error, but the technique can be used as a complement to increase the total accuracy of the combined systems [28, 48].

2.3 Combined DGPS/INS System

To obtain greater accuracy than the DGPS provides, several systems use a combination of a DGPS unit and an IMU. To increase the position accuracy between DGPS samples inertial gyros and/or accelerometers are used to calculate the new

³See Appendix A.2 for carrier wave information.

⁴The performance is valid for kinematic measuring. Static measuring obtains even better accuracies.

⁵See Appendix B for more information.

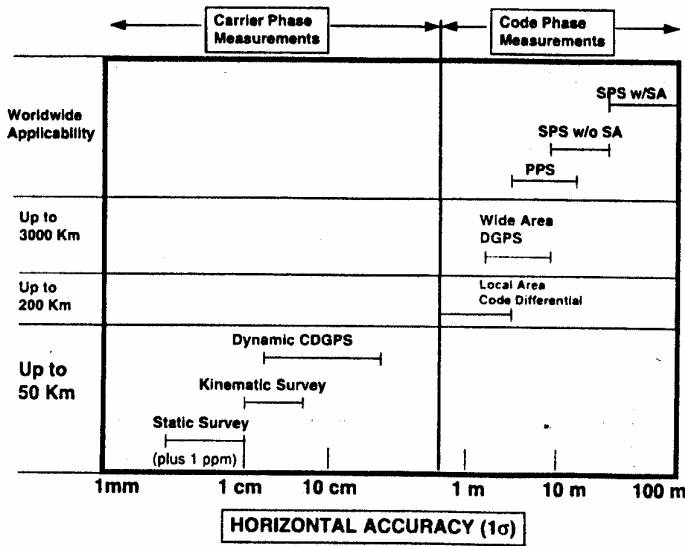


Figure 2.2. Summary of expected differential GPS concepts and position accuracies [48].

position. Due to the DGPS combination, the system will not suffer from severe drifting in the calculation of the new position. After every new DGPS sample, the inertial system has a known position to calculate from. This technique can deliver position with a very high sample rate (e.g. 250 Hz [39]). When adding a Kalman filter to this setup, the system obtains even greater resolution. The Kalman filter uses the input errors to give the system an even more exact position. The standard deviation is below 2 cm in some products⁶. To further improve the position accuracy a single/double antenna GPS, differential GPS correction, and an IMU unit can be used. See Figure 2.4 for a block diagram of DGPS/INS unit. The input to the figure is the measured value of the gyros and accelerators [47, 48].

The ordinary use of this technique in the automotive industry is to measure vehicle handling (roll-, pitch-, yaw-angles⁷, slip, etc) [47]. A combined DGPS/INS system would be an appropriate choice for this application, but this technique leads to very expensive hardware.

2.4 Vision System

This section presents different vision systems that are used for automotive implementation such as collision avoidance, adaptive cruise control, and lane detection systems. Vision systems can be used for positioning with reference points by measuring distance and heading to the reference points.

⁶See Appendix G for example.

⁷See Figure B.1

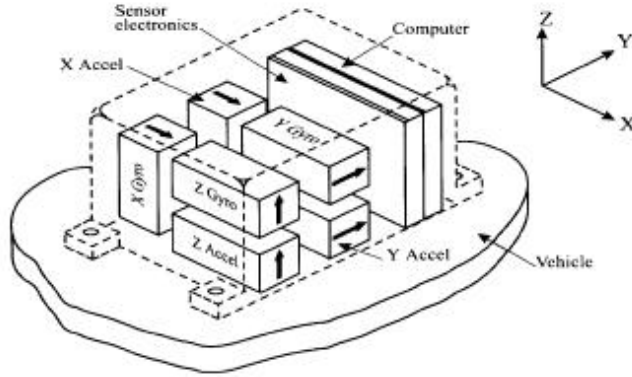


Figure 2.3. A schematic drawing of a Inertial Navigation System (INS). The system contains gyros and accelerometers to obtain information in three dimensions and a computational unit to process the information signals.

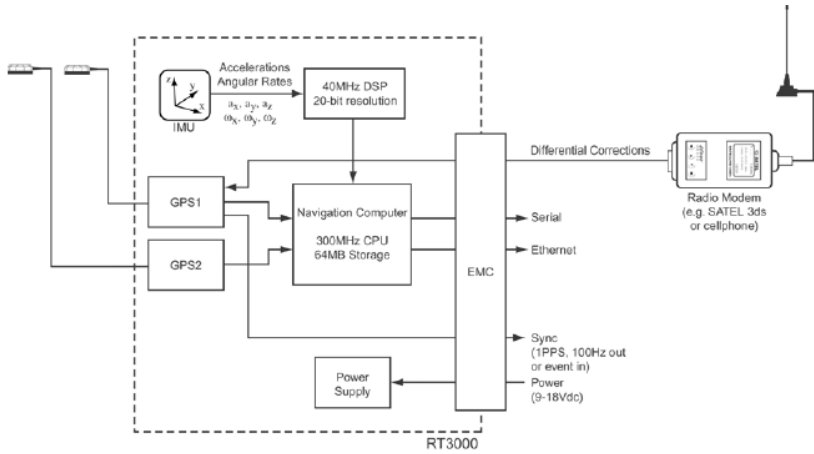


Figure 2.4. Schematic block diagram of a combined DGPS and INS unit. The computational unit combines the information from the GPS receiver (single or dual antenna), the INS system, and receives differential correction signals from a differential base station via the radio modem. All this information supplies the user with a high accuracy in position [47].

Table 2.1. Accuracy of different navigation types

Navigation Type	Theoretical performance
GPS	≈ 15 m [1]
GPS with EGNOS	≈ 2 m [19]
GPS L1 Carrier Phase	1.8 m [42]
GPS L1\ L2 Carrier Phase	1.5 m [42]
OmniSTAR GPS	sub m [42]
Local Area DGPS L1 Carrier Phase	0.45 m [42]
Local DGPS L1\ L2 Carrier Phase	sub dm [42]
Local DGPS L1\ L2 with INS	sub dm [47]

2.4.1 Line Following Systems

A system that is commonly used by Automated Guided Vehicles (AGVs) is the line following principle. By using a guidance system the vehicle can follow a predefined guidance line by itself. Vehicles with monotonous driving schedules are suited for this system. The principle of implementation is usage of a vision system (e.g. a laser scanner) that detects a significant marking or reflection material and uses it as guidance. This technique can also be implemented with magnetic force, which the PATH project (see Appendix C.1) in California is one example of. Using permanent magnets in the roadway and detectors in the vehicle results in a robust system. However this technique suffer from problems as relocation and mobility of the system, due to the need of static implementation [49]. Due to our demands of movability of the system, this technique is not of interest to our needs.

2.4.2 Camera Systems

Camera systems can use one or several cameras in combination with a computer to perform image processing. The camera systems can give a very high resolution, and advanced target classification is possible thanks to the detailed images. The camera systems are very dependent on good light conditions and free sight of view. Darkness and weather conditions as rain and snow, lower the resolution of the images which leads to lower reliability of the camera system. When combined with infrared, or thermal, cameras the system can see in the dark. Such camera systems suffer from reflection of heat radiation which makes it hard to use within navigation and safety purposes. The image processing algorithms are computation intensive which may make it difficult to maintain reliability when the environment changes rapidly (such as at high speed driving) [31]. Advantages and disadvantages of this system are presented in Table 2.2.

2.4.3 Radar Sensors

Radio detection and ranging (*Radar*) is one of the most common tracking sensors. It has been used for automotive purposes, such as adaptive cruise control. A radar emits electro-magnetic radiation to illuminate targets. It uses the same antenna to

Table 2.2. Camera system [31]

Advantages	Disadvantages
Cost efficient system	Sensitivity to light conditions
High resolution	Sensitivity to dirt and weather
Advanced target classification	High computational demands

Table 2.3. Radar system [31]

Advantages	Disadvantages
Bad-weather performance	Bad resolution
Automotive usage	Clutter
Range	Ghost and multipath reflections

emit as to receive, by switching between sending and receiving mode. It sends out a conical lobe that is reflected by the object. To obtain information about the target, the system receives an echo of the emitted signal and can calculate the distance to the target. One sensor can do a mechanical sweep, or electronically switches can be used to alternate between different sensors, each located at different emission angles. These techniques make it possible to survey a wider area. In general for automotive purposes the field of view is 10° - 15° . For short distances (less than 200m), the radar has good performance in bad-weather conditions, e.g. darkness, rain, haze, and snow. Although good performance, the resolution to verify the objects' identities is not very good due to the wide lobe. For this project, the radar needs assistance of other devices to obtain acceptable performance. The radar suffers from unwanted reflections called clutter. Reflections from the road surface might give "ghost" obstacles. Multipath propagation might also occur. The precision of the radar is not suitable as a stand alone implementation of navigation. The best use of this application would be as an Automatic Cruise Control (ACC) system [31]. Advantages and disadvantages of this system are presented in Table 2.3.

2.4.4 Laserscanners

The laser scanner (also known as *Lidar*) works like a radar. A laser pulse with a defined duration is sent and reflected by an object. The reflection of the object is captured by a photo diode and transformed into signals in an optoelectronic circuit. The time interval between the pulse of light being sent and its reflection being received indicates the distance to the object which reflected the light. In addition to the radar, the laser pulse is quite narrow. This gives the laser scanner a higher resolution of the object.

By rotating a mirror, the laser range finder operates as a scanner and the mirror deflects each outgoing beam. The mirror's continuous rotation, in conjunction with the pulsing laser, generates a complete environmental profile of the vehicle

within the laser scanners visible range (see Figure 2.5). The laser scanning system has been adapted by several autonomous prototype vehicles. The lidar technique has also been implemented by Volvo Technology at their Volvo Integrated Safety Truck (see Appendix C.4.2). Usage of the lidar is for example collision avoidance, pedestrian safety, blind spot surveillance [31].

Lidar Performance

The laser scanner has a very high sample rate. This makes it suitable for scanning the environment at high speeds. This technique is similar to millimeter-radar (mm-radar), but is a less expensive technique to use. The range and the narrow lobe of the laser makes the system very precise. It provides a high resolution of the pixel map and could give more detailed information than the mm-radar. The laser scanner system is also very tolerant to clutter. Again, the narrow beam does not suffer from reflections of nearby objects in the same degree as a radar [31].

The intensity of the reflected laser pulse can be detected by the lidar and can easily be projected into a gray scale picture. This is very useful to implement in the lane detection feature (see Figure 2.6). The laser scanner is relatively insensitive to the surrounding light conditions [31, 35, 58, 54].

Despite all of these advantages, the laser scanner suffers from a couple of weaknesses. In the automotive industry, most of these systems are at prototype stage. This makes the price high at this stage, but will probably drop when prototypes go to large series production. In similarity with the camera system the laser scanner must have a free line of sight. Rain and fog could also interfere with the correct echo detection. A single pulse can be reflected by rain or other weather obstacles. Due to the technique of reflection the lidar has difficulties to detect dark and rough objects. These objects are hard to detect due to absorption of the laser beam. The lens also needs to have a clear view to avoid false detections [31, 43].

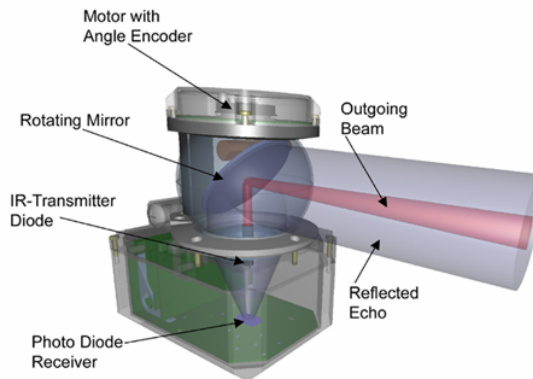


Figure 2.5. An exploded view of a laserscanner. The laser beam is reflected on to a rotating mirror to spread the view of sight. The echo of the laser beam is received and the distance and the heading can be calculated [26].

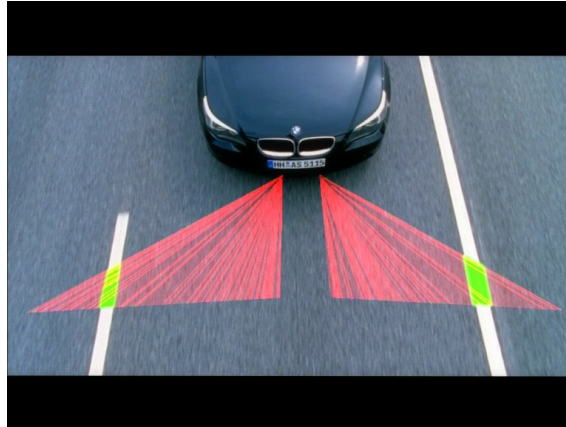


Figure 2.6. Animation of the principle of lane detection using a laserscanner [26]

Lidar Technique

The lidar vision system uses several different techniques to increase its performance. Dirt on the lens could result in a false detection. The dirt reflections can to a certain extent be filtered by processing the signal. This applies to limited surface elements. The obstacles of the lidar, such as bad weather performance is improved by using four-echo technology. An object, such as a raindrop or another vehicle, would normally generate one reflection or echo per laser pulse. By increasing the number of echoes to as many as four per pulse, and by filtering the echoes and removing the false echoes, the lidar has significantly optimized and refined object detection [26]. For implementation at a truck that is supposed to drive under very rough road conditions, the system is exposed to hard oscillation. The system handles this problem with a multilayer technique (see Figure 2.7). The laser beam is split into four different layers and the distance measurements are taken independently for each of these layers with an aperture angle of 3.2° . This allows compensation for pitching of the vehicle, caused by an uneven surface or driving manoeuvres such as braking and accelerating. Since the beam, generated by each laser pulse, is split into four layers, the lidar sensors can evaluate the data from the reflections (up to 16 reflections per measurement, four echoes and four layers). This technique gives a high grade resolution and reliability [24].

All products are in a prototype stadium. A truck implementation is available as well as the possibility to produce products according to customer specifications. The scan of the surrounding environment detects objects, due to the many reflection points, in a high resolution picture. This also results in that the detected object can be identified by its significant structure. The detected objects can be assigned with an ID number, a velocity, and a heading. Due to the high scanning frequency a high resolution model of the surrounding environment can be estimated. In the model can objects be classified as a car, a truck, a pedestrian, a fixed object, etc. By using the heading and distances to known objects, navigation



Figure 2.7. Example of a multilayer lidar. The lidar beam is spread in different angles to obtain additional information of the surroundings.

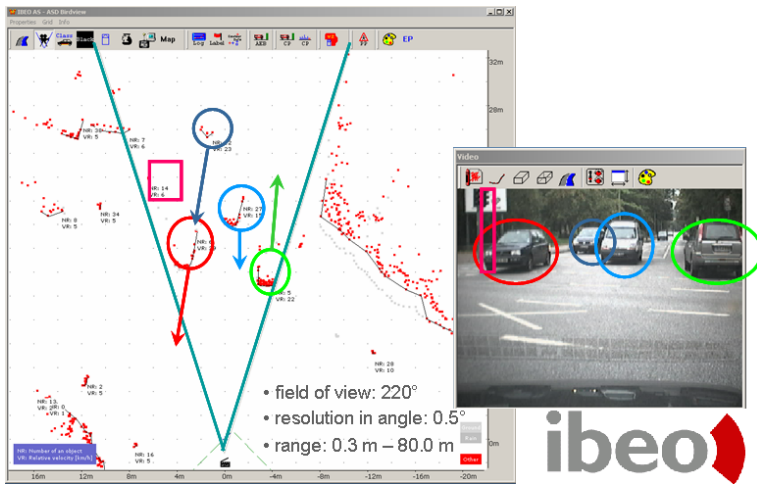


Figure 2.8. Lidar object detection. The picture to the left shows the lidar echoes of the surrounding environment corresponding to the right picture.

is possible. In Figure 2.8 the different cars' velocity and headings are marked with circles and arrows. The fixed object is marked with a square. In the picture to the left, it is shown how the lidar detects objects and different contours in the surrounding environment. The precision of the position can also be increased when using precise high level maps [62]. Detection of the lanemarkings can also be used for road navigation and vehicle control [13, 35, 37].

An installation of two laser scanners in the front of the truck will give a satisfying visual coverage to prevent collisions and the ability to navigate by nearby objects (see Figure 2.9). The lidar function and performance is suitable as a vision system to an autonomous system. The lidar system is used for safety applications by many developing companies and is frequently used by the D.A.R.P.A.⁸ autonomous vehicles [6, 26]. Advantages and disadvantages of the system is presented in Table 2.4.

⁸The D.A.R.P.A (Defense Advanced Research Projects Agency) is the central research and development organization for the U.S. Department of Defense (DoD)[7].

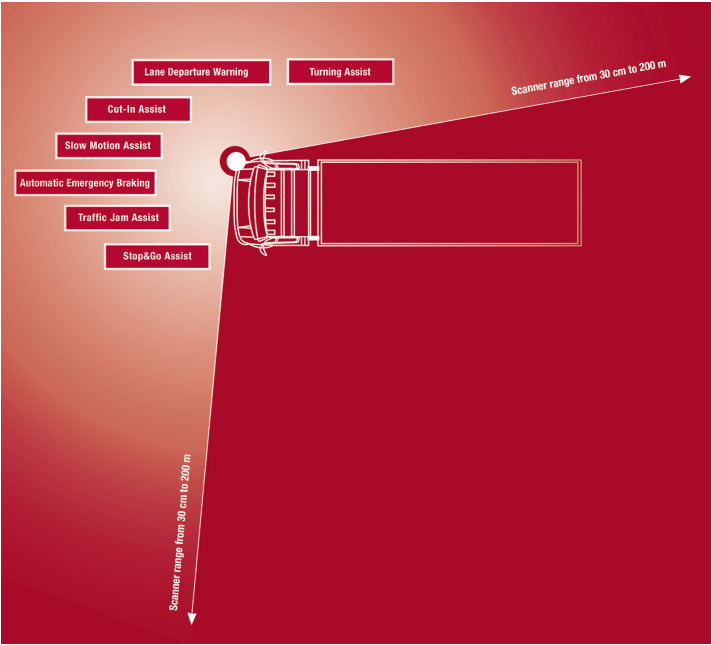


Figure 2.9. Field of vision of a laser scanner mounted on the right front of a truck. By using this location, the scanner covers approximately 270° of view [26].

Table 2.4. Lidar system [31]

Advantages	Disadvantages
Resolution	Dirt sensitivity
Minimal clutter	Weather sensitivity
Light insensitive	Prototype stadium
Photo detection	
Used in automotive application	

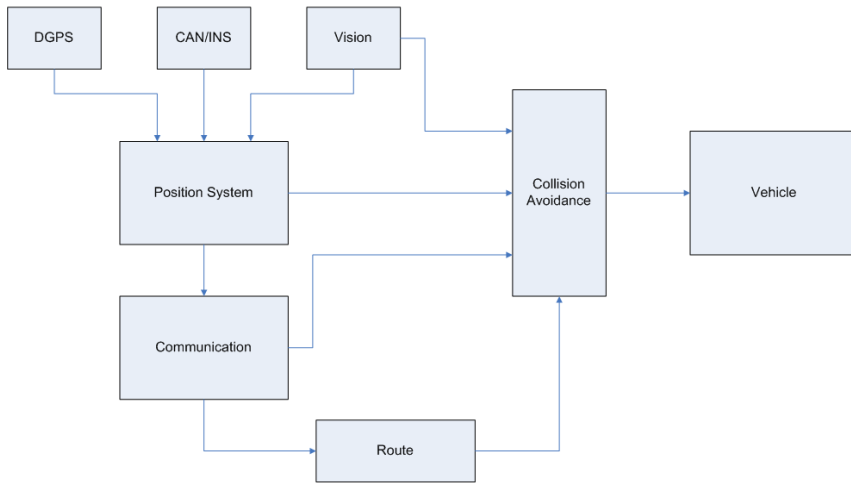


Figure 2.10. An extended system structure to run autonomously. To obtain accurate position, the position system uses information from DGPS, CAN/INS, and from a vision unit.

2.5 Complete Position System

To fulfill the demands of the problem specification in Chapter 1.3, the performance of the CDGPS is of interest as a positioning system and will be further investigated. The input signals to the position system will in this stage be from a DGPS, the CAN (Controller Area Network) information, and from the vision system. A block diagram over the system principle is presented in Figure 2.10. The vision system that, at this point, seems to have the most advantages is the lidar system. By integrating the lidar vision with the DGPS, the vehicle's position system increases its robustness [25].

Chapter 3

Communication Systems

The complete system is depending on a communication system in order to implement interacting between vehicles. To surveil the traffic of the test track the communication system will be used to upload and download information about the vehicles states. In this chapter several techniques will be presented and investigated as to the possibility to obtain the wanted performance.

3.1 STDMA

STDMA stands for Self organizing Time Division Multiple Access. This method was developed by Håkan Lans and is used for positioning and identification of aircrafts (VDL Mode 4) and ships (AIS). The STDMA data link is divided into a number of time slots to send data messages. It is self organized and the communicator can by itself find a free slot and send the message to the free slot. Every node must have access to global time and the regular transmissions are sent as "heartbeats". This means that different types of data can be sent on the data link, using just one frequency. All communicators within radio distance will be able to hear the message. The STDMA scheme ensures that access is free of collisions and that the bandwidth per node is guaranteed [18, 23, 33].

3.1.1 VDL Mode 4

VDL Mode 4 (Very high frequency Data Link Mode 4) is the standard of the International Civil Aviation Organization (ICAO). The main purpose for VDL Mode 4 is to send an Automatic Dependent Surveillance Broadcast (ADS-B) signal to complement the ground radar and the surveillance service. The technique is also used as a Flight Information Service Broadcast (FIS-B). It sends the aircraft's position and identification to all surrounding aircrafts. It can also send complementary information, such as weather information, from the control tower to the aircraft. The data link transmits digital data in a standard 25 kHz VHF communication channel [2, 18, 23, 33].

The problem with this is that the total bandwidth is limited due to the number of slots that can be used. This results in a limited number of users and/or a small amount of data that can be sent [2, 18, 23, 33].

3.1.2 TACSYS/CAPTS

The Taxi and Control System/Cooperative Area Precision Tracking System (TACSYS/CAPTS) is an innovation project from Fraport AG. The general function of this system is to increase the accuracy of airport ground navigation in poor weather conditions. It uses the signals from the on-board transponders. By measuring the time of the incoming transponder signals the distance to the object can be calculated by triangulation. The transponder signal includes an ID-tag so the identity of the vehicle also can be determined [4].

3.1.3 STDMA Summary

The STDMA technique, e.g. VDL-Mode 4, is a very robust and reliable communication system. It has been approved by the aeronautical industry, which shows out its reliability. Because of the system's limitations in transfer rate and in the number of vehicles that can simultaneously use it, this system is not interesting for our application. The future expansion possibilities would also be narrowed down and the possibility to send larger amounts of data would be limited.

3.2 Wireless Local Area Network

3.2.1 IEEE 802.11

IEEE 802.11x is the standard of Wireless Local Area Network (WLAN). The IEEE 802.11 is followed by an index letter (a,b,g,n¹ in this case) which indicates what version of WLAN it is. In table 3.1 the capacity and performance of different 802.11-protocols is presented. This is the most common communication technique adapted for wireless data transfer.

Table 3.1. IEEE 802.11x specifications of frequency and transfer rate

Protocol	Operation Freq.	Transfer Rate
802.11a	5 GHz	54 Mbit
802.11b	2.4-2.5 GHz	11Mbit
802.11g	2.4-2.5 GHz	54 Mbit
802.11n	2.4 and/or 5 GHz	248 Mbit

¹802.11n is a draft version.

3.2.2 WLAN With Dual Antennas

A problem with the WLAN-technique is that latency occurs when switching between different Access Points (AP). When leaving the area of AP_i and entering the area of AP_j , the receiving module must do a scan to obtain a new signal. This causes a latency time when the receiver does not have a wireless connection. To minimize this latency time, the receiving unit can be equipped with a dual antenna system. A normal latency time for a single antenna (including roaming) is about 1 second. By adding one antenna to the system, it can decrease the handover time to approximately 60 milliseconds with fast authentication [44]. One technique of the dual antenna handover theory is presented in the following subsection.

Handover Theory

If a Mobil Node (MN) is equipped with a dual antenna system the handover time can be reduced. The system has to work with two WLAN InterFaces (IF_1 and IF_2). The MN uses these two different IF's for data communication and for searching for new AP. These two IF are switched alternately, e.g. when IF_1 is communicating, IF_2 is searching for a better AP. When connection is established, IF_1 is searching and IF_2 is communicating. To make a connection to the next AP, the system must satisfy the condition:

$$P_c - P_p > P_t$$

where

- P_c = Power level in dBm of candidate AP radio signal
- P_p = Power level in dBm of used AP radio signal
- P_t = Power level in dBm of predefined threshold

Then IF_2 can establish a connection and authentication to the next AP. During this authentication processes, IF_1 is still active in a receive-mode only for a certain protection time. When the protection time is over, IF_1 is disconnected and starts searching for another AP. Using this overlapping sequence, the system completes the handover with minimal package loss. The handover flowchart is presented in Figure 3.1 [44].

One solution to speed up the handover process is to shorten the authentication time and the location registration time. The Mobile Switch (MS) authenticates a MN on behalf of the radius server when the MN switches from AP_i to AP_j . After establishing an air link, the MN sends an authentication start request. Then, the MS generates a key that is used to maintain the identity of the MN for the following process. The MN sends an authentication message to the MS that includes a response word derived from the key. The MS forwards it to the radius server as a radius authentication message. The radius server then authenticates the MN and sends back a response message. After this authentication the MS confirms that the MN is identical to what was previously authenticated. The MS compares the key from the previous transaction and if the key is verified there is no need to do a transaction to the radius server (see Figure 3.2) [44].

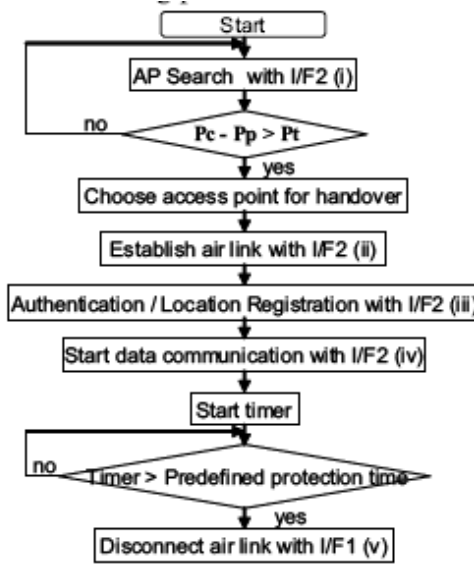


Figure 3.1. Flowchart of the handover process using dual antenna technique. This schematic flow describes how the system switches between the two network interfaces [44].

3.2.3 Selective Channel Scanning

The IEEE 802.11b/g works with several different channel frequency distributions. In Sweden the channel distribution is according to Figure 3.3 and the distribution is divided to 14 possible channels, but several of these are overlapping. Among these channels only three of them are not overlapping, and together they cover the entire bandwidth. These channels are 1, 6 and 11. To reduce the scanning time and decrease the handover time it is possible to use a selective scanning procedure. It takes less time to scan three channels instead of fourteen. This is called a selective scan [53].

3.2.4 Handover Using Neighbour Graph

To make a faster handover it is possible to use a technique that builds and sends out a Neighbour Graph (NG). A NG is an undirected graph where each edge represents a mobility path between two AP's [40, 41].

Definition 3.1 (Neighbour Graph)

$$G = (V, E)$$

$$V = \{\{v_i : v_i\} = (AP_i, channel) \in \{AP_1, AP_2, \dots, AP_i\}\}$$

$$e = (AP_i, AP_j)$$

$$N(AP_i) = \{AP_{ik} : AP_{ik} \in V, (AP_i, AP_{ik}) \in E\}$$

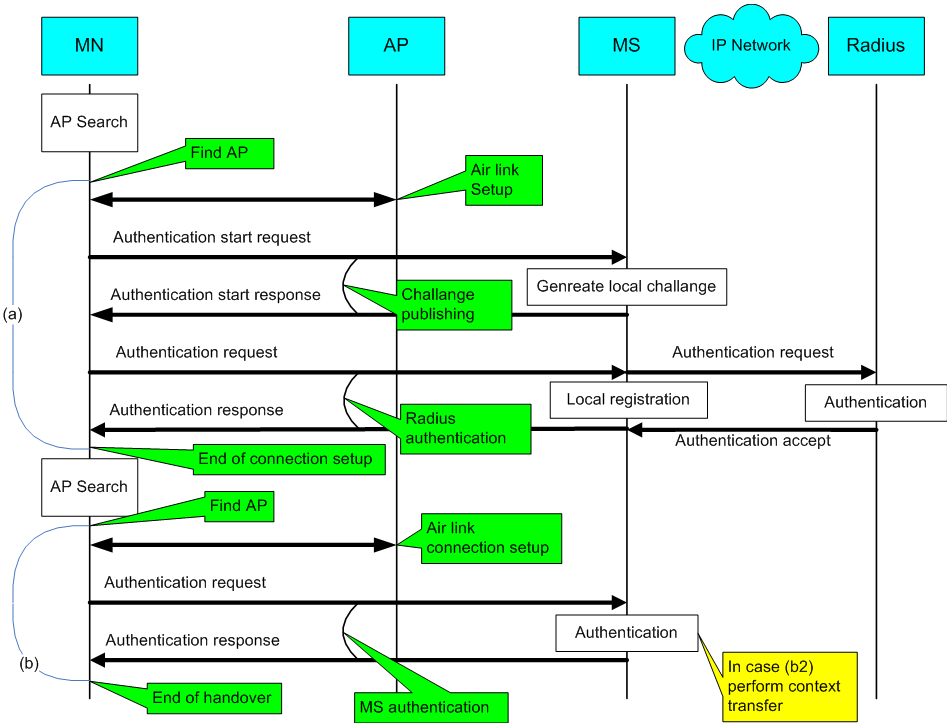


Figure 3.2. Fast authentication when switching between two APs. The flowchart describes how the authentication requests and responses are handled.

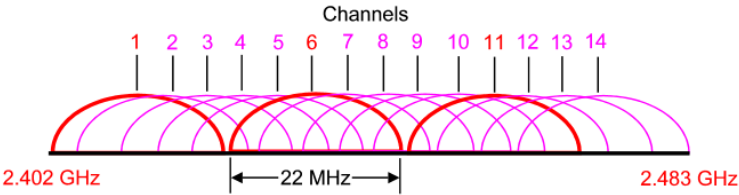


Figure 3.3. Channel frequency distribution in IEEE 802.11b [53]

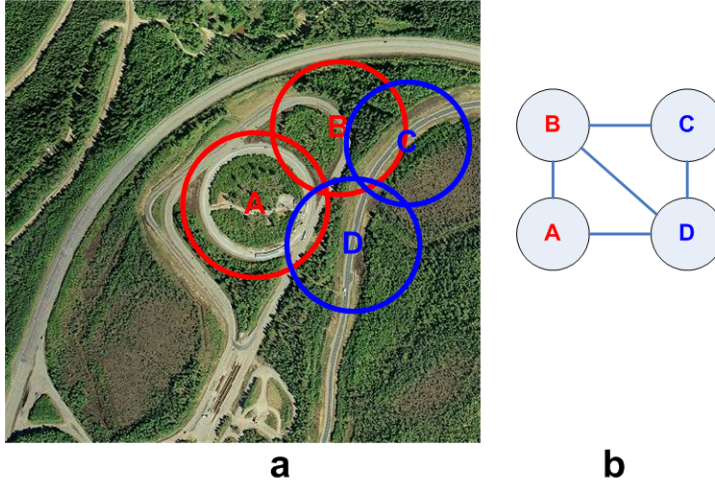


Figure 3.4. (a) Map of an AP's example positions. (b) Neighbour graph corresponding to the AP's position in (a).

where G is the data structure of NG , V consists of AP's and their channels, E is the set which consists of edge (e), and N is the neighbor AP's of a AP [40, 41].

A simple example of a possible AP placement and its corresponding neighbor graph is shown in Figure 3.4.

The NG can be generated by two different methods. The first uses the reassociation request from the mobile node. The reassociation request contains MAC² address of the old AP. The second way to build the NG is to use the *Move-Notify* message³ [36, 40].

Both the reassociation request and the *Move-Notify* message adds an edge to the NG. The first mobile node to change from AP_i to AP_j will suffer from a high latency, but the cost of this is amortized over all upcoming changes from AP_i to AP_j . If the network is restarted the NG-info can be loaded from a file with the latest known NG [40, 41].

When no mobile node hand-offs from AP_i to AP_j is done in a given time interval T , the edge should be removed from the NG [40, 41]. The major advantage of an automatically generated NG is adaption to changes in the AP placement, physical topology, AP malfunction, etc.

Figure 3.5 shows an example of a simple flowchart of an NG server and in Figure 3.5 b the corresponding flowchart of the NG client is shown [36].

²Media Access Control

³An Inter AP Protocol (IAPP) message that are used to reduce link layer handoff latency [38]

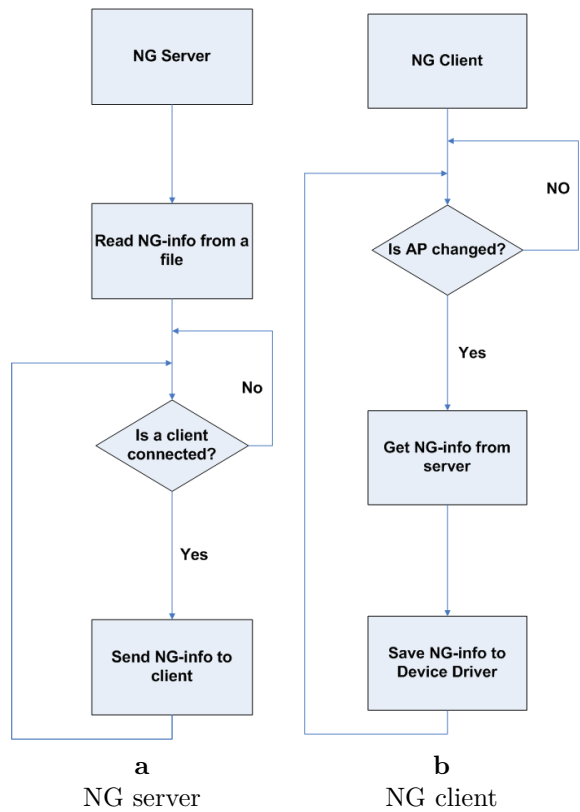


Figure 3.5. Flowchart of the NG server and NG client.

3.2.5 IEEE 802.11 Summary

The IEEE 802.11 technique offers "off the shelf technology". This is a very common technique used both by professionals and by the general public. The widespread popularity of these products makes the price low and the accessibility high, which is a major advantage of this products. It is a widespread technique and with increasing performance. Adoption of this technique for automotive use (fore example roadside systems) points to an effective range of 150 m in radius [46]. This features makes the IEEE 802.11 technique very interesting as a communication tool. The problem is the limited range of the system.

3.2.6 ZigBee

ZigBee is a high level communication protocol which is based on the IEEE 802.15.4 standard. It is a low-power radio based solution for wireless personal area networks (WPANs). The advantages of the ZigBee is low power consumption, giving a long

life battery, and secure networking. The disadvantage are on the other hand that the data rate is low and the product is not approved as a standard [8]. This technique is not suitable to use as a communication device due to the low data rate.

3.2.7 WiMax

Worldwide Interoperability for Microwave Access (WiMax) is the standard IEEE 802.16. The use of WiMax is to cover large areas with wireless access, approximately 70 Mbit/second over 500 km. It operates between the 2.5 GHz and the 5.8 GHz frequency band. The main purpose of this system is to provide the final user with a wireless connection without cable connection. In Sweden it operates in the licensed frequency band of 3.5 Ghz. This has to be licensed from the *Post- och telestyrelsen (PTS)* [64]. This technique supports a great range but is not intended for implementation as a closed network in a small area. The implementation is not cost efficient and the interface would be difficult to implement. This makes the technique not suitable for our needs.

Chapter 4

Collision Avoidance

Collision avoidance is a common aspect in the automotive industry nowadays. The preventative work is to reduce the numbers of traffic accidents. Today most collision avoidance systems are driver assisting/warning systems, e.g. Adaptive Cruise Control (ACC), Lane Departure Warning (LDW), Blind Spot Surveillance (BSS), etc. By installing vision units in the vehicle to gather information about the surrounding environment, the driver can obtain this information to reduce the risk of ending up in a hazardous situation. By using sensor-target-tracking algorithms and prediction models (e.g. state-space prediction), the surrounding vehicles can be assigned with relative position and heading. This information is validated to get a threat assessment of the situation [17]. Work is also done to receive information from other nearby vehicles and road side units. The theory is often applied in intersections where peer-to-peer networks are used to establish connections. In these situations vehicle positions and traffic information (e.g. stop signs, traffic signals etc.) are exchanged [14, 15].

The environment of a test-track is similar to the standard traffic environment as well as the basic functions of a collision avoidance system. The major differences between these situations are that the test track has more restrictions of the drivers (the drivers are professionals), more restricted traffic rules, limited number of vehicles, etc, and the advantage of providing the vehicle with suitable equipment for a specific scenario. The test track is also a closed area and does not allow any unknown vehicles. These specific test track features simplifies the implementation of a collision avoidance system. All vehicles can be equipped with suitable tools (in this case communication devices and positioning systems). As mentioned in Chapter 3 all vehicles are able to communicate with each other (server based communication) and all vehicles will also have a position system to calculate the vehicles' positions. The server based communication supplies every user with information about all other vehicles states (such as position, heading, velocity, etc.). When this information is known the tracking and state estimation of the vehicles is unnecessary.

The basic conditions of the collision avoidance system in this thesis can be summarized in Figure 4.1. The flowchart shows an example of how a suggested

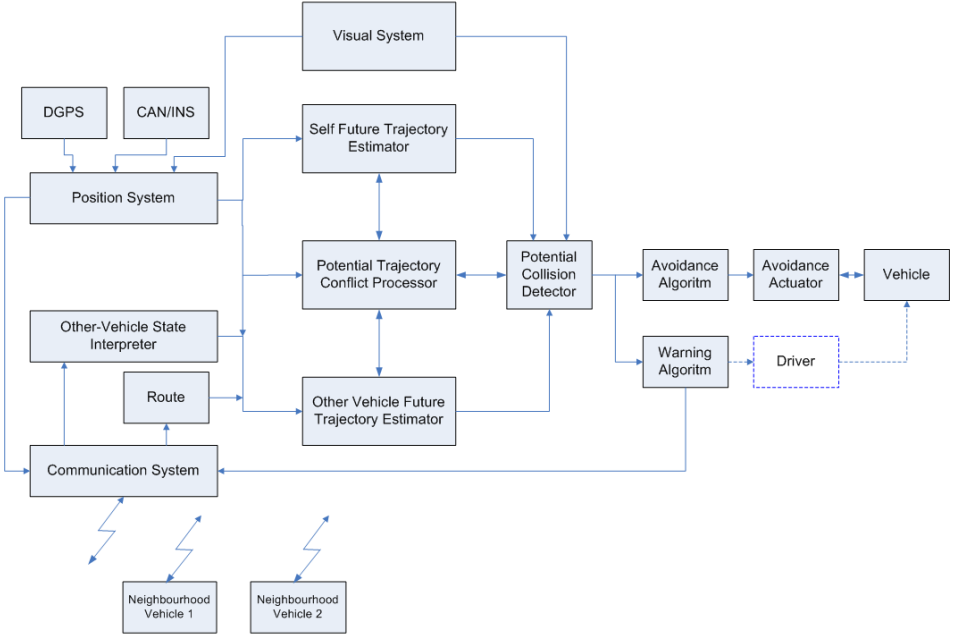


Figure 4.1. Flowchart of Collision Avoidance System in the complete system. The flowchart shows how the subsystems are connected and how they exchange information with each other.

collision avoidance system could be implemented. This flowchart is an extension of the flowchart in Section 2.5 and it has been divided into several subsystems.

All vehicles on the test track will have a communication device combined with a trajectory prediction to estimate all other vehicles positions. An autonomous vehicle also needs a vision system to take care of the unpredictable objects that could occur (e.g. animals and items that are blocking the roadway).

4.1 Collision Avoidance Prediction

The prediction of the vehicle's position is intended to estimate the risk of a future collision. By using a model of the vehicle motion, the future position can be predicted. There are several vehicle models that can be used for prediction of the position with different degrees of complexity (e.g. general models and vehicle specific models that handles vehicle dynamics) [31, 34, 60].

One of the simplest vehicle model is the constant velocity model given in Equation (4.1) and (4.2). This model describes a straight line between two measurement updates. The model is based on four states as position (x and y) and constant velocity in both directions (ν_x and ν_y). This model will be used in some examples in this report to show the principle of collision avoidance when the vehicle states are known.

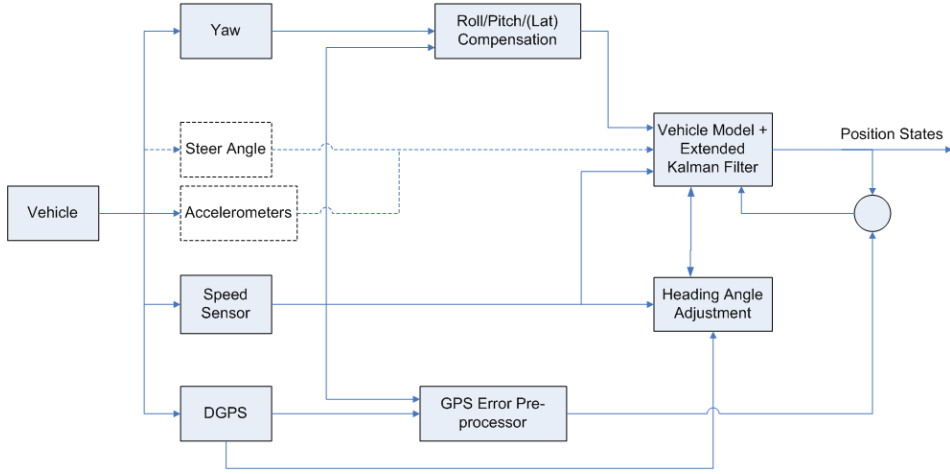


Figure 4.2. Block diagram of the position states estimator

$$X(t_i) = \begin{bmatrix} x(t_i) & y(t_i) & v_x(t_i) & v_y(t_i) \end{bmatrix}^T \quad (4.1)$$

$$X(t_{i+1}) = \begin{bmatrix} 1 & 0 & (t_{i+1} - t_i) & 0 \\ 0 & 1 & 0 & (t_{i+1} - t_i) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} X(t_i) \quad (4.2)$$

All vehicle states are calculated by the vehicle itself and then transmitted to all other vehicles which leads to the errors in the states being less than when these states have to be estimated by the other vehicle. Another advantage is that the vehicle does not need visual contact with the other vehicles to track and estimate their future positions. Since all vehicles receive the vehicle states from the other vehicles, the prediction will be the same, independent of which vehicle that does the prediction. An example flowchart of how the states can be calculated is shown in Figure 4.2.

When the states are known a prediction can be done. By comparing the prediction of a vehicle with the surrounding vehicles, a future possibility of a collision can be predicted. If the vehicle model and the measurement of the states are really good, an implementation of a collision avoidance system can be done by assigning a safety area around the vehicles. When these areas overlap each other the system will alert. An example of this is shown in Example 4.1.

— **Example 4.1: Ideal linear prediction with fixed safety distance** —

Two vehicles are traveling in the nearby area. Both are estimated with a constant velocity model (see Equation (4.1) and (4.2)). The two vehicles each have a preset safety radius, in this example these are set to four and six meters. The vehicle initial states are given as below:

$$X_1(t_0) = \begin{bmatrix} 0 & 0 & 10 & 0 \end{bmatrix}^T$$

$$X_2(t_0) = \begin{bmatrix} 0 & -55 & 10 & 10 \end{bmatrix}^T$$

The predicted positions are presented in Figure 4.3. If both vehicles continue with present headings and velocities, there is a great probability that a collision will take place after five seconds. The future predictions in this case require a perfect model and state estimation.

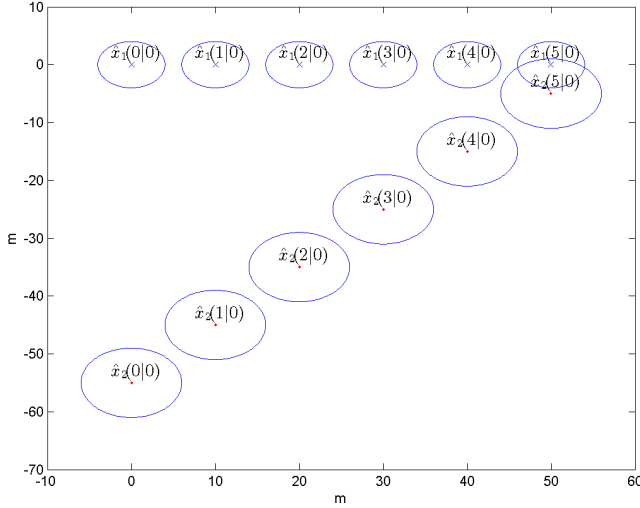


Figure 4.3. A linear prediction from the present position at $\hat{x}(0|0)$. Circles around every prediction symbols the fixed safety distance. At state $\hat{x}(5|0)$, the two position estimations with corresponding safety distances will indicate a possible collision.

In Example 4.1, the model as well as the measurement are assumed to be very good and are not very realistic. Almost all state measurement equipments have some kind of errors (see Table 2.1 for typical GPS accuracy) and this insecurity should be taken into consideration. In Example 4.2, an error in the position is assigned and the safety area is then increased in each step.

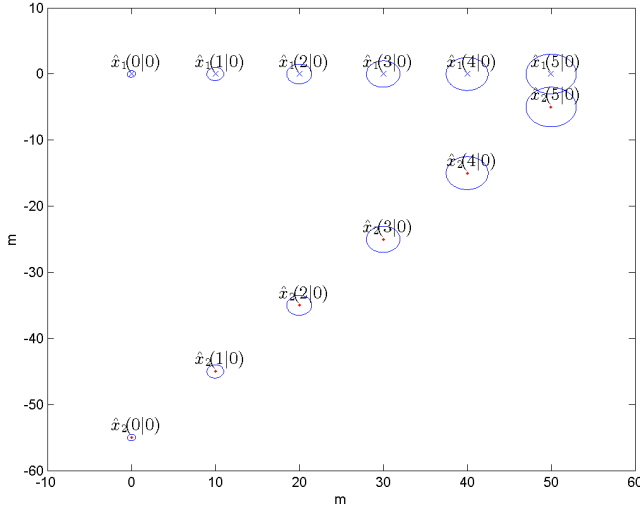


Figure 4.4. Linear prediction with increasing prediction error. In every prediction, the safety distance is increased. Circles around every prediction symbols the safety distance. At state $\hat{x}(5|0)$, the two position estimations with corresponding safety distances will indicate a possible collision.

Example 4.2: Linear prediction with error in position

The situation is identical to the situation in Example 4.1 and the vehicle states are the same. The vehicle position has an error due to uncertainty in the position system. This will lead to a greater uncertainty of the future predicted positions. The probability of a future collision will also increase. The error in position is defined as $\sigma_x^2 = 0.5m$ and $\sigma_y^2 = 0.5m$.

To cover the predicted area with a safety distance, the radius is enhanced for every step in time. By using the standard deviation to predict the worst case scenario, an area could be calculated with $\sigma_{x,y}^2 \cdot k$. An example is showed in Figure 4.4.

Another technique to estimate the future position is to use the Kalman m-step prediction. By calculating the error covariance matrix (P) and the state vector $\hat{x}$ (see Algorithm 1) and then performing the m-step prediction (see Algorithm 2) with these variables, the future states can be estimated. This calculation also considers the given state and measurement errors (Q and R). If the noise is assumed to be Gaussian it can be shown that the equation $g = (x(t+m|t) - \tilde{x}(t+m))^\top [P(t+m|t)]^{-1} (x(t+m|t) - \tilde{x}(t+m))$ is a χ^2 distributed variable [12, 29]. In Example 4.3 a Kalman m-step prediction is done.

Algorithm 1 Kalman filter (KF)

Initial values:

$$\begin{aligned}\hat{x}(0| - 1) &= x_0 \\ P(0| - 1) &= \Pi_0\end{aligned}$$

Time update:

$$\hat{x}(t + 1|t) = A_t \hat{x}(t|t) \quad (4.3a)$$

$$P(t + 1|t) = A_t P(t|t) (A_t)^T + Q_t \quad (4.3b)$$

Filter gain computation:

$$L(t) = P(t|t - 1) C_t^T [C_t P(t|t - 1) C_t^T + R_t]^{-1} \quad (4.4)$$

Measurement update:

$$\hat{x}(t|t) = \hat{x}(t|t - 1) + L(t)(y(t) - C_t \hat{x}(t|t - 1)) \quad (4.5a)$$

$$\begin{aligned}P(t|t) &= P(t|t - 1) - \\ &P(t|t - 1) C_t^T [C_t P(t|t - 1) C_t^T + R_t]^{-1} C_t P(t|t - 1)\end{aligned} \quad (4.5b)$$

where

$$\begin{aligned}Q_t &= Cov(w_t) \\ R_t &= Cov(e_t)\end{aligned}$$

Algorithm 2 Kalman filter, m step predictor

$$\hat{x}(t + m|t) = A^m \hat{x}(t|t) \quad (4.6a)$$

$$P(t + m|t) = A^m P(t|t) (A^m)^T + \sum_{k=1}^m A^{m-k} Q (A^{m-k})^T \quad (4.6b)$$

Example 4.3: Kalman prediction

By using the constant velocity vehicle model (see Equation (4.1) and (4.2)) and the Kalman filter m-step prediction (see Algorithm 2), the future estimated position and a confidence region around that prediction can be calculated. The constant velocity model has been extended with process and measurement noise according to the following equations.

$$x(t+1) = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \omega \quad (4.7)$$

and

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} x + \zeta \quad (4.8)$$

where ω is normal distributed and has a covariance ($\sigma_{x,y} = 0.5$, $\sigma_{v_x,v_y} = 0.1$)

$$Q = \begin{bmatrix} \sigma_x & 0 & 0 & 0 \\ 0 & \sigma_y & 0 & 0 \\ 0 & 0 & \sigma_{v_x} & 0 \\ 0 & 0 & 0 & \sigma_{v_y} \end{bmatrix}$$

and ζ has the covariance

$$R = \Gamma \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4.9)$$

where Γ is small (0.0001) due to the communication possibilities. To determine if the system should warn about a future collision risk, some definitions need to be explained (see Figure 4.5). When the safety distance between two vehicles is defined as D_{th} , it is of interest to know if two vehicles are separated with at least D_{th} . When the noise is assumed to be Gaussian, the confidence region around $x(t)$ can be calculated. Due to the Gaussian noise the confidence region $g = (x(t+m|t) - \hat{x}(t+m))^T [P(t+m|t)]^{-1} (x(t+m|t) - \hat{x}(t+m))$ is a $\chi^2(n)$ distributed variable where n is the dimension of x .

To determine the probability of the confidence region, a position $x(t+m|t)$ must be assigned. In this example the position we have chosen is the edge of the ellipse with a radius of $R_{calc} = \max\left(\frac{D_{th}}{2}, \frac{D-D_{th}}{2}\right)$. In the Figure 4.6, the confidence region is plotted and the corresponding probability is shown in Table 4.1. If the probability is less than a given threshold, an indication of a future hazard situation will be made. This indication can also be weighted with the step number (m). A smaller m is a prediction in the near future and due to prediction errors it is a much greater risk for collision than if m is larger.

Table 4.1. Position probability when using the Kalman prediction.

State $x(t)$	$P\left(x(t) \leq \frac{D-D_{th}}{2}\right)$
$x(0 0)$	$\geq 99\%$
$x(1 0)$	$\geq 99\%$
$x(2 0)$	$\geq 99\%$
$x(3 0)$	$\geq 99\%$
$x(4 0)$	$\approx 50\%$
$x(5 0)$	0 due to $D \leq D_{th}$

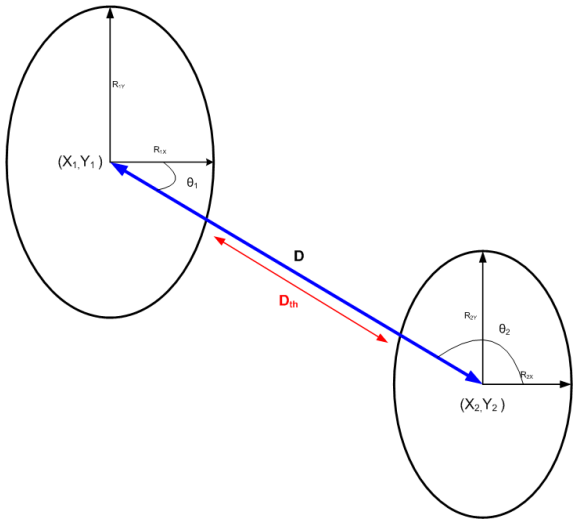


Figure 4.5. Distance and angles defined for the Kalman prediction example.

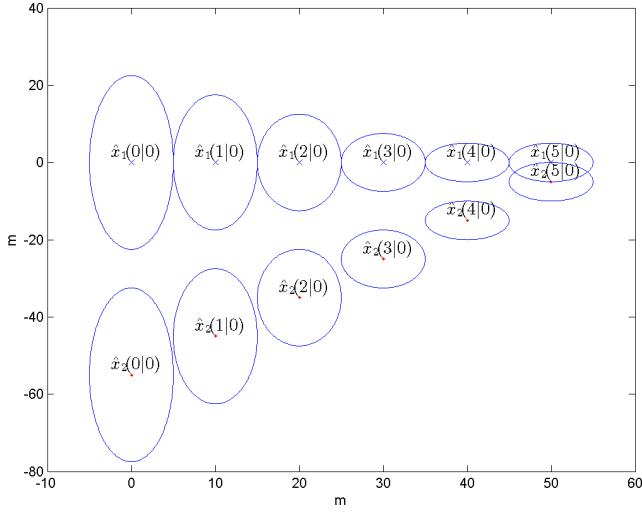


Figure 4.6. The Kalman position prediction. In every prediction, the confidence region is calculated according to $R_{calc} = \max\left(\frac{D_{th}}{2}, \frac{D-D_{th}}{2}\right)$. With this information the system is able to calculate the probability of the position estimation being within this region. At state $\hat{x}(5|0)$, the two position estimations with corresponding confidence region will indicate a possible collision.

As shown in Example 4.1-4.3, the position prediction are exactly the same due to no difference in the model. The difference of using the Kalman prediction is that this technique handles the error in a more realistic way. Another advantage of the Kalman technique is that the confidence interval of the prediction is χ^2 -distributed.

The vehicle model that is used in these examples is, as mentioned, very simple. Increasing the model to a non-linear model also increases the accuracy of the calculated positions. The side effects are that the CPU-time increases and an extended Kalman filter has to be used (see Appendix E for information of an extended Kalman filter technique). The choice of model will depend of computing capacity and demands of accuracy. By comparing very simple models, an indication can be given of how the accuracy and computational demands are combined. By running several Monte-Carlo simulations (1000 MC simulations) and comparing the average path on each model (Constant velocity, Constant acceleration, and Nearly coordinated turn¹), a grade of computational load can be achieved. An example is presented in Table 4.2 [31].

By using non-vehicle dependent models, it is very easy to adapt the system to a wide range of different vehicles. This increases the versatility of the system. As seen in Table 4.2, the maximum error of for example the nearly coordinated turn model (3.5 m) is acceptable as the safety radius will be greater than this distance. In Equation (4.10)-(4.12) a suggested vehicle model is presented. The suggested vehicle model is similar to the nearly coordinated turn model. In the model, the variables x and y are earth inertial coordinates, φ is the heading angle, ν_x is the longitudinal velocity, $\dot{\psi}_z$ is the yaw rate, $\dot{\psi}_b$ is the bias in the yaw rate measurement, and $\eta_{\dot{\psi}_b}$ is a white Gaussian noise. This is a general model that is independent of vehicle handling parameters. This model has shown good accuracy in position and good performance in prediction [60]. By using this kind of model, it is easy to assign it to a great number of different vehicle's and it makes the system very versatile due to the independence of the vehicles models. The accuracy could of course be increased by extending the model with vehicle specific parameters, but the versatility of the model and the accuracy should be enough for the intended function as a collision avoidance predictor [59, 60].

¹See [31] for more information about given vehicle models.

Table 4.2. Vehicle model errors and CPU time [31]

Model	RMSE ² [m]	Max error [m]	CPU time
Constant velocity	0.88	5.2	1
Constant acceleration	0.65	4.7	1.2
Nearly coordinated turn	0.56	3.5	2.8

$$\begin{aligned}
X(t_i) &= \begin{bmatrix} x(t_i) & y(t_i) & \varphi(t_i) & \dot{\psi}_b(t_i) \end{bmatrix}^T \\
X(t_{i+1}) &= \begin{bmatrix} x(t_i) + (t_{i+1} - t_i)\nu_x(t_i) \cos \varphi(t_i) \\ y(t_i) + (t_{i+1} - t_i)\nu_x(t_i) \sin \varphi(t_i) \\ \varphi(t_i) + (t_{i+1} - t_i)(\dot{\psi}_z(t_i) - \dot{\psi}_b(t_i)) \\ \dot{\psi}_b(t_i) + \eta_{\dot{\psi}_b}(t_i) \end{bmatrix} \quad (4.10)
\end{aligned}$$

The vehicle's current states estimates as an initial state $X_p(t_n, 0)$ and the vehicles future states are $X_p(t_n, t_p)$, $(0 \leq t_p \leq T_{pred})$ where T_{pred} is the total prediction time. The model based prediction is given by Equation (4.11) where $f(X, U, t_n, t_p)$ is a nonlinear model and $U_p(t_n, t_p)$ is the assumed future input.

$$\dot{X}_p(t_n, t_p) = f(X_p(t_n, t_p), U_p(t_n, t_p), t_n, t_p) \quad (4.11)$$

When the vehicle's current states are given, the accuracy of the prediction depends on the assumption of driver input and the vehicle model. To increase the accuracy of this prediction, the history of the driver and future driving schedule could be incorporated. With constant input assumption, the prediction model based on the vehicle model (in Equation (4.10)) is showed in Equation (4.12), where $(\dot{\psi}_z - \dot{\psi}_b)$ is the unbiased yaw rate and $(a_x - a_b)$ is the unbiased longitudinal acceleration [59, 60].

$$\begin{aligned}
X_p(t_n, t_p) &= \begin{bmatrix} x(t_n, t_p) & y(t_n, t_p) & \varphi(t_n, t_p) & \nu_{xp}(t_n, t_p) \end{bmatrix}^T \\
X(t_n, t_{p+1}) &= \begin{bmatrix} x(t_n, t_p) + (t_{p+1} - t_p)\nu_{xp}(t_n, t_p) \cos \varphi(t_n, t_p) \\ y(t_n, t_p) + (t_{p+1} - t_p)\nu_{xp}(t_n, t_p) \sin \varphi(t_n, t_p) \\ \varphi(t_n, t_p) + (t_{p+1} - t_p)(\dot{\psi}_z(t_n) - \dot{\psi}_b(t_n)) \\ \nu_{xp}(t_n, t_p) + (t_{p+1} - t_p)(a_x(t_n) - a_b(t_n)) \end{bmatrix} \quad (4.12)
\end{aligned}$$

4.2 Vehicle States Message

To calculate a prediction of a vehicle, the vehicle states of the particular vehicle must be known. According to Equation (4.12), the time, position (Lat, Long), vehicle speed (v_x, v_y) , heading (φ) , yaw rate $(\dot{\psi})$, and the longitudinal acceleration (a_x) are demanded. This demanded information could be gathered in an information message, the Vehicle States Message (VSM), and sent to other surrounding vehicles. This message can also include an *ID tag*, *Track*, and an *Information Message*. This information can be used to specify the vehicle, discard non-relevant vehicles, and obtain vehicle status (running autonomously, brake down, hazard situations, etc.). A suggested content of a VSM is presented in Table 4.3. The total length of this suggested message is 157 bits. According to the IEEE 802.11 standard, the general MAC³ header with checksum is 30 Bytes [10]. This means that the entire frame is less than 50 Bytes.

³Media Access Control

Table 4.3. Vehicle State Message

Message information	Range	SI unit	Number of bits
Time	[00:00:00.00,23:59:59.99]	<i>Seconds</i>	25
Lat	[0.000 000,90.000 000]	<i>Degree</i>	27
Long	[0.000 000,180.000 000]	<i>Degree</i>	28
North/South	North = 1, South = 0		1
West/East	West =1, East = 0		1
Speed	[0.00,100.00]	<i>m/s</i>	14
Heading (φ)	[0.0,360.0]	<i>Degree</i>	12
Yaw rate ($\dot{\psi}$)	[-40.95,40.95]	<i>Degree/s</i>	13
Acceleration (a_x)	[-20.00,20.00]	<i>m/s²</i>	12
ID	[0,255]		8
Track	[0,255]		8
Information Message	[0,255]		8

4.3 Collision Avoidance Vision

A part of the collision avoidance system is the trajectory prediction technique. This is implemented for all vehicles (autonomous and with human drivers). Even if every vehicle has a communication system, a positioning system, and has connection with everyone, an unpredictable object can occur on the test track. An animal can run across the roadway, a truck can lose its trailer, a vehicle can break down, etc. A vehicle with a human driver can react to this scenario and do an avoidance manoeuvre but an autonomous vehicle has to be extended with a vision system. For collision avoidance systems several different vision techniques are used. The systems that we have been investigating are presented in Chapter 2.4.

The demands of the vision system in this case is to achieve a satisfactory field of view (about 180°) and detect objects in front of the vehicle. An ACC radar sensor has normally a 15° field of view [31], but with this performance demand a fusion unit (several sensors) or a custom specified radar must be used. The lidar system has a greater field of view as well as the fusion unit. A single lidar covers approximately 170° and a fusion unit (placed on each front corner) covers approximately 300° [20, 26]. Figure 4.7 shows an example plot of a single lidar detection area. The lidar is mounted on a truck's front left corner. The dotted line points out the field of view of a single lidar. The reflected image shows a detection of a car in front of the vehicle. The high resolution makes it possible to identify the object due to its significant structure. A fusion system also increases the redundancy of the complete system. The data that is collected from the same area makes it possible to verify the view of the front of the vehicle (the most relevant area in the collision avoidance system) with a second measurement. The sensor fusion also features as a backup if malfunction in one sensor should occur [13].

A general feature in automotive collision avoidance systems is the possibility of object tracking. The vision unit (e.g. radar or lidar) detects the object and

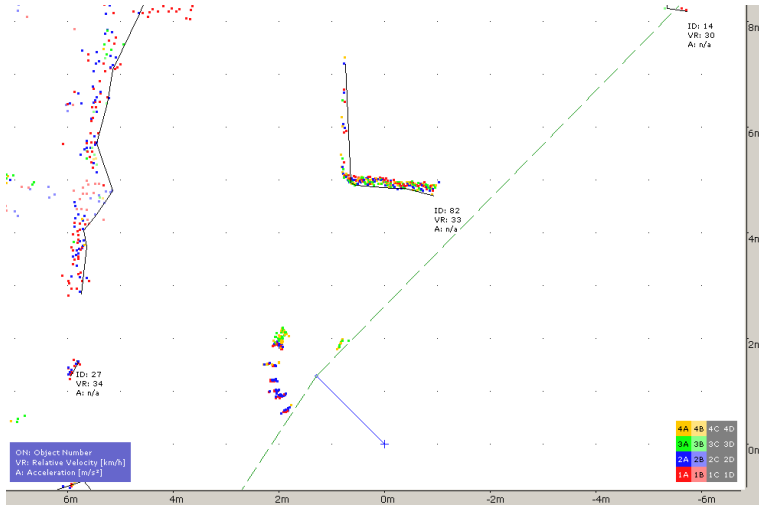


Figure 4.7. A front edge mounted laser scanner. The picture shows the echoes and how the unit detects an object (in this case a car) in front of the vehicle

can observe a range to the object, a range rate measurement (e.g. by Doppler shift), and an azimuth angle to the object. By estimating the vehicle states, a prediction of the new position can easily be done. The predicted position can then be used to determine how an avoidance manoeuvre should be implemented. This is a feature that is relevant to use in regular traffic scenarios where every surrounding vehicle is unknown [37]. In the case of test track environment and surrounding conditions, the vehicle already has all the relevant vehicle states (from the communication) and all vehicles are known. When surrounding vehicles states are unknown, a tracking feature has to be implemented to observe the vehicles states. Due to the already known vehicle states, a more precise prediction can be done when the position and heading does not have to be estimated. Hence this tracking feature can improve the avoidance manoeuvre if an unknown object appears, e.g. an animal, a trailer, or a broken down vehicle. Further information about tracking can be found in [11].

Chapter 5

Measurements and Data Collection

In this chapter measurements and data collections that have been made during the thesis are presented. The chapter will also cover analysis of the collected data and signals.

5.1 GPS coverage

In this section the result of GPS coverage measurements is presented. It will cover the results of long time static measurements, dynamic measurements at the tracks at Hällered test site. Analysis of the GPS accuracy will also be handled.

5.1.1 Static GPS Coverage Hällered

To verify that the GPS coverage at Hällered is satisfactory, data was collected during one week (see Table 5.1) with a stationary GPS receiver. The NMEA GGA sentence (the NMEA sentence is specified in Appendix A.2) was monitored. The receiver was placed with free sight in the Southern hemisphere direction. In this test, a USB connected GPS receiver was used with a specification according to Appendix F. In the GGA sentence contains several fields to determine the GPS coverage (numbers of satellites) and quality (HDOP) of the GPS signal. To obtain an accurate position the GPS receiver needs at least four satellites (see Appendix A.2) and it needs to have an HDOP value below four for excellent satellite constellation (see Appendix A.2).

Figure 5.1 shows is the number of satellites. It seems like it is several added sinus waves with a large period time. To obtain a clearer signal, the signal is filtered through a low pass Butterworth filter of the fourth degree with a cutoff frequency of 10 mHz. In Figure 5.2, the filtered signal is plotted and the corresponding frequency spectrum obtained through FFT¹ calculation is shown in Figure 5.3.

¹FFT=Fast Fourier Transform

Table 5.1. Stationary GPS measurement

	From	To
Date	03/07/07	10/07/07
Time	13:30	13:30

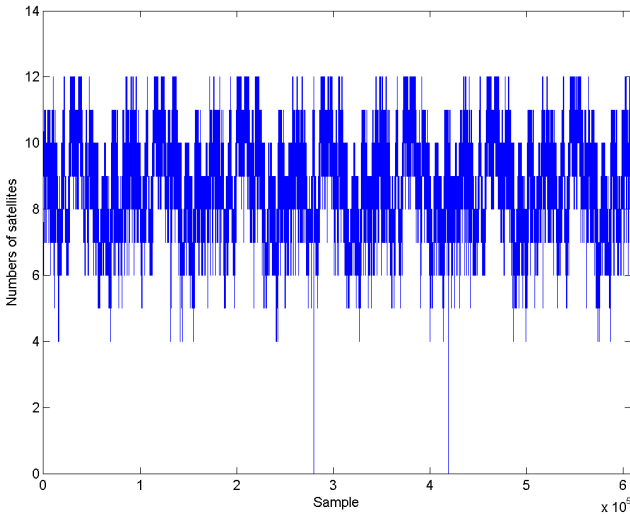


Figure 5.1. Number of satellites at Hällered sampled at 1 Hz during one week.

The frequency spectrum shows four major frequencies where the shortest period time is approximately 24 hours.

The HDOP value recieved during this time is plotted in Figure 5.4 and the figure shows that the value variates between approximately one and seven.

The conclusion from static measurements at Hällered is that the satellite coverage is satisfactory, but the HDOP value sometimes exceeds over the recommended for excellent satellite constellation.

5.1.2 Test Track GPS Coverage

The different test tracks at Hällered are surrounded with trees (see aerial photo in Figure 5.5). Therefore it is important to investigate if there are any GPS shadows on the test track due to the vegetation and/or the topography. A GPS antenna was placed on the center on the roof of an estate car and the NMEA GGA sentence was logged during the test. The test was performed by driving laps on every single lane of the test track to detect GPS shadows. The results are shown in Figure 5.6 and Figure 5.7. The results shows that the numbers of satellites and the HDOP

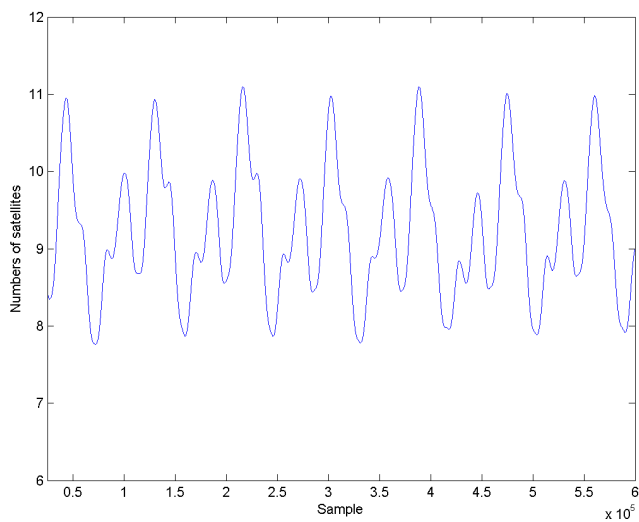


Figure 5.2. Low pass filtered signal of the number of satellites at Hällered sampled at 1 Hz during one week.

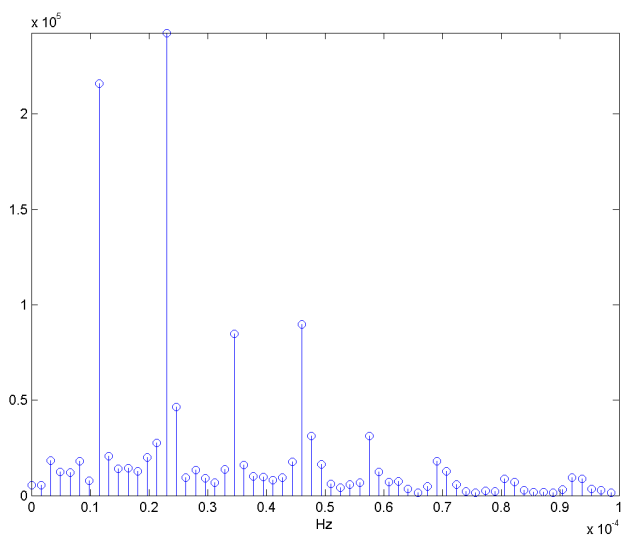


Figure 5.3. Frequency spectrum of the low pass filtered signal in Figure 5.2.

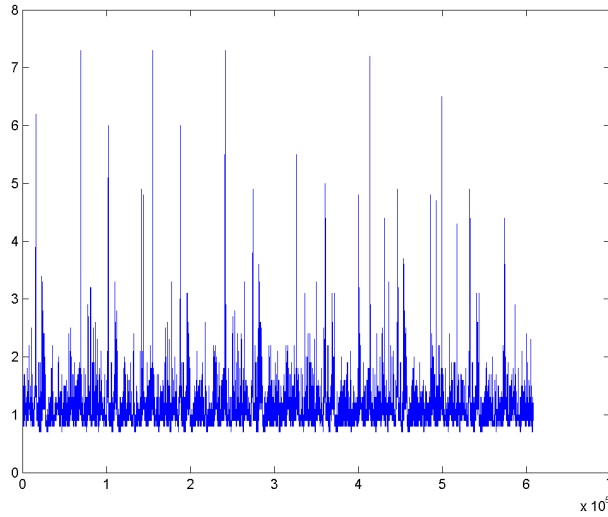


Figure 5.4. HDOP signal measured at Hällered sampled at 1 Hz during one week.

values are satisfying the demands for GPS navigation. With this result we know that the tracks due not have any sections that suffer from GPS shadows. This result shows that there should be no problem to use GPS as a positioning tool.

5.1.3 GPS Accuracy

To verify the GPS accuracy, three long-time, each one week of duration, measurements were made, one measuring at Hällered and two at Lundby. The GPS receiver (see Appendix F for GPS receiver specifications) was located within clear Southern hemisphere sight and mounted on a stationary platform. During the measurements, the number of satellites was always at least four. Figure 5.8 shows the position measured at Hällered plotted and Figure 5.9 - 5.10 the position measured at Lundby.

In Table 5.2 the drift is presented in meters ($\max^2$, $\min^3$ and the standard deviation (σ)). The distances between the points of interest where calculated using the haversine formula (see Appendix D.1).

The standard deviation of all long-time measurements is close to the given accuracy by the GPS manufacturer⁴, but the maximum drift is almost fifteen times higher. For autonomous positioning and navigation, both the standard deviation and the maximum drift is of interest. Because the maximum drift is approximately fifteen times higher than the standard deviation the lateral, longitudinal, and

² $\sum_{i=1}^n \frac{x_i}{n} + \max\{x_1, x_2, \dots, x_n\}$ where n is the number of samples

³ $\sum_{i=1}^n \frac{x_i}{n} - \min\{x_1, x_2, \dots, x_n\}$ where n is the number of samples

⁴The GPS resolution given by the GPS manufacturer is the standard deviation



Figure 5.5. Aerial photo of Hällered test site.

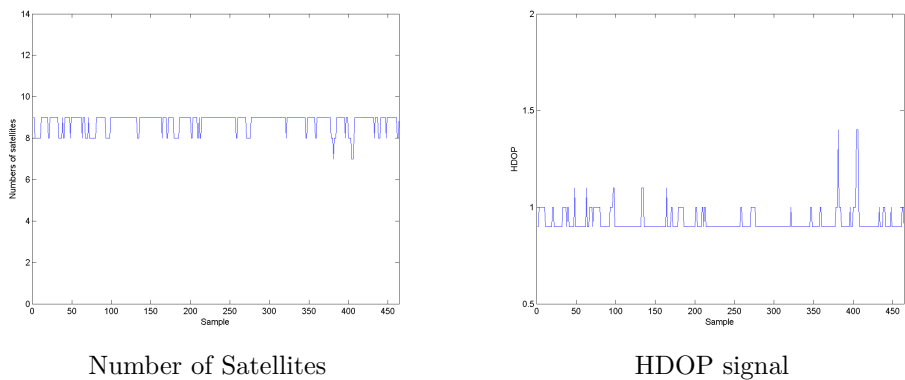


Figure 5.6. GPS measurements sampled at 1 Hz on the Life Endurance Track.

Table 5.2. The GPS accuracy

	Hällered		Lundby 1		Lundby 2	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
Min	67 m	63 m	110 m	30 m	186 m	30 m
Max	161 m	47 m	65	17 m	94 m	70 m
σ	10 m	10 m	9	4 m	10 m	5 m

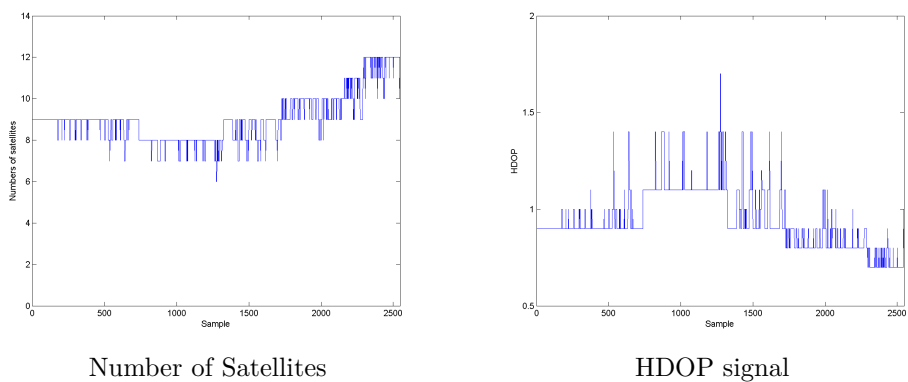


Figure 5.7. GPS measurements sampled at 1 Hz on all tracks. The measured signal has no indication of any GPS outage.

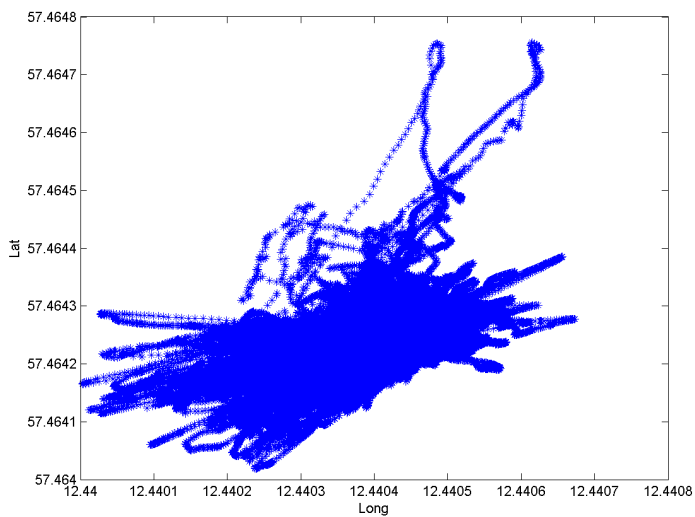


Figure 5.8. Stationary GPS position measured at Hällered during one week.

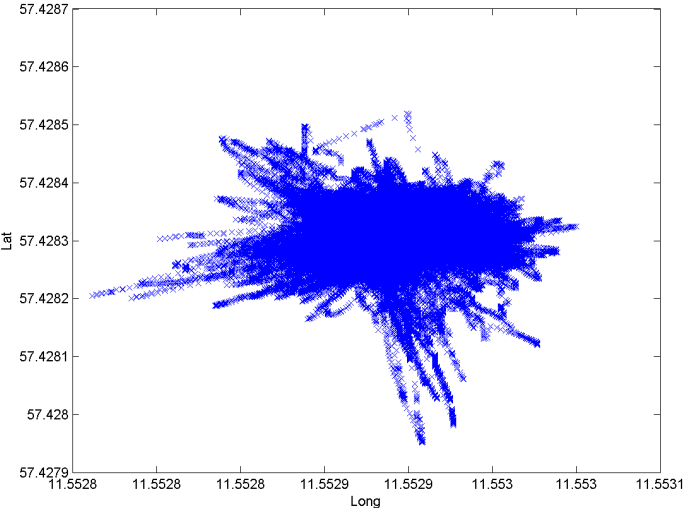


Figure 5.9. Stationary GPS position measured at Lundby (1)

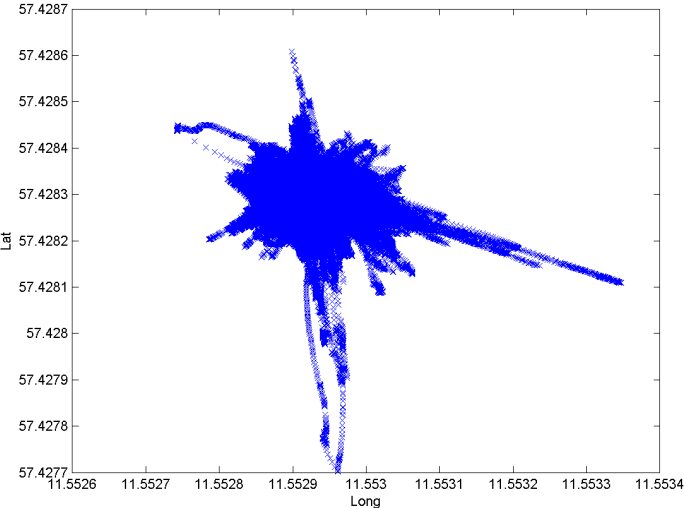


Figure 5.10. Stationary GPS position measured at Lundby (2)

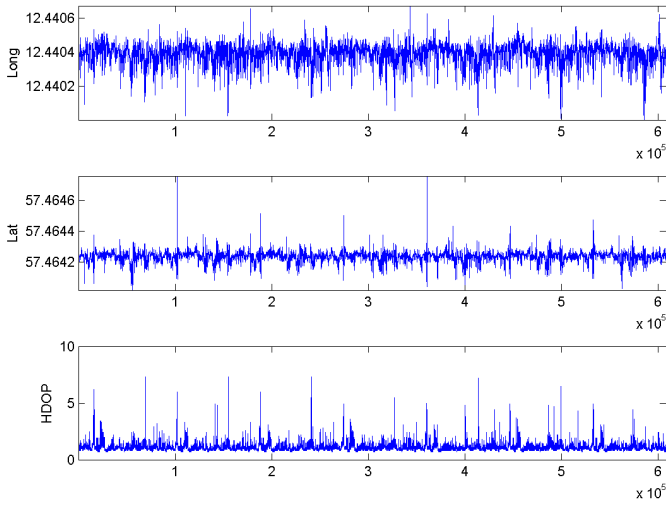


Figure 5.11. Lat, Long, HDOP signals from Hällered.

HDOP signal is plotted in Figure 5.11 - 5.13. The figures shows that the position seems to drift away when the HDOP value gets high. To reduce this position error we have investigated if the position gets any better by removing some samples when the HDOP value exceeds a given limit. In Figure 5.14 - 5.16 the result is plotted and by removing approximately 300 samples the standard deviation is reduced by approximately ten percent.

5.1.4 Dual GPS

The results in the static measurements indicated a drift in the static position. By using two simple identical GPS receivers (data sheet in Appendix F) and logg the measurements simultaneously, to investigate if both receivers were drifting to the same position. In that case it might be possible to use one of them as a local differential station. To see if the position varied together we investigated the correlation (see Appendix D.2 for more information about these calculations) of the signals. The results are presented in Table 5.3. It shows that the correlation is small and that the signals do not follow each other closely. Due to the poor result of this test the conclusion is that these GPS receivers are not suitable for obtaining a local area correction.

5.1.5 Differential GPS

The test performed with a typical GPS receiver showed poor performance. To verify if the cause of the poor performance was the hardware, a test using a high

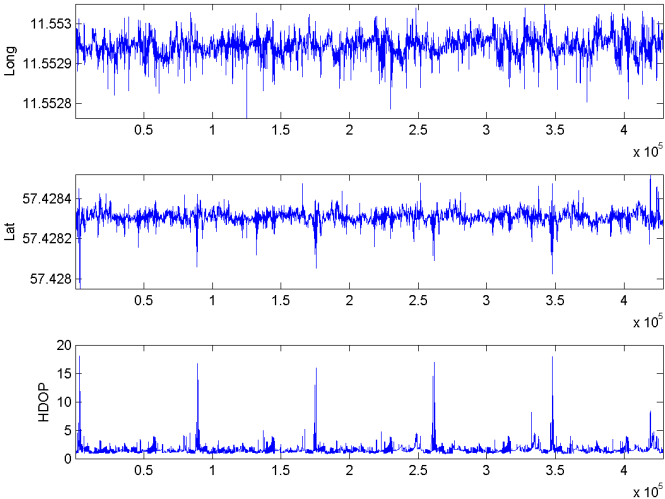


Figure 5.12. Lat, Long, HDOP signals from Lundby 1.

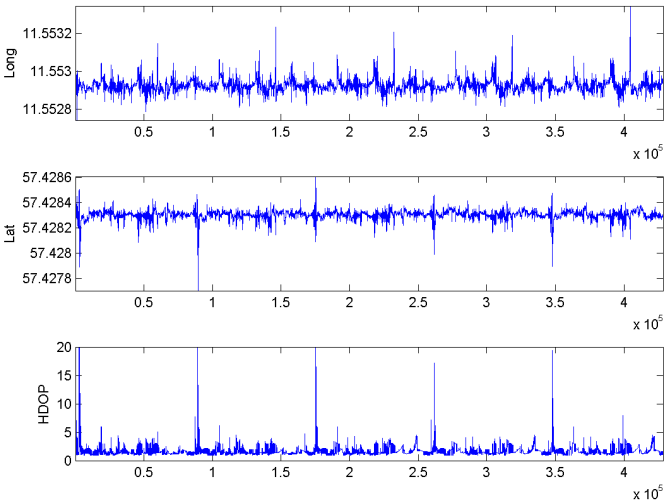


Figure 5.13. Lat, Long, HDOP signals from Lundby 2.

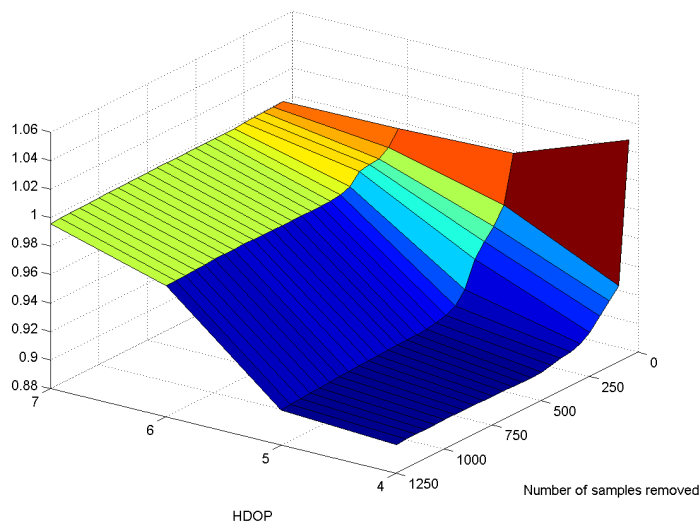


Figure 5.14. Standard deviation improvement by removing samples for which HDOP exceeds the given level (Hällered).

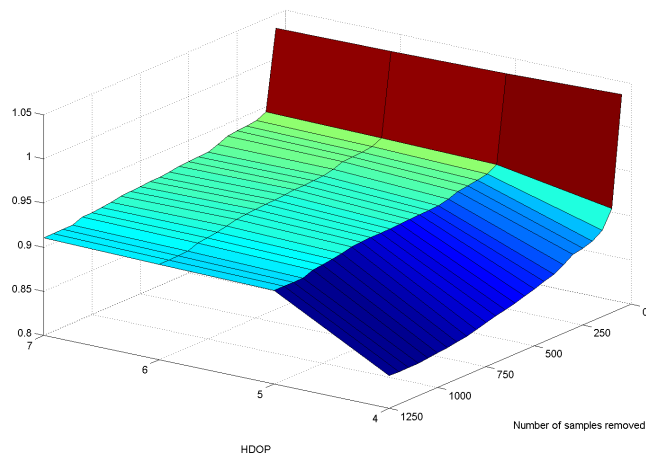


Figure 5.15. Standard deviation improvement by removing samples for which HDOP exceeds given level (Lundby 1).

Table 5.3. Correlation between the signals

Lateral		Longitudinal	
1.0000	0.3053	1.0000	0.2434
0.3053	1.0000	0.2434	1.0000

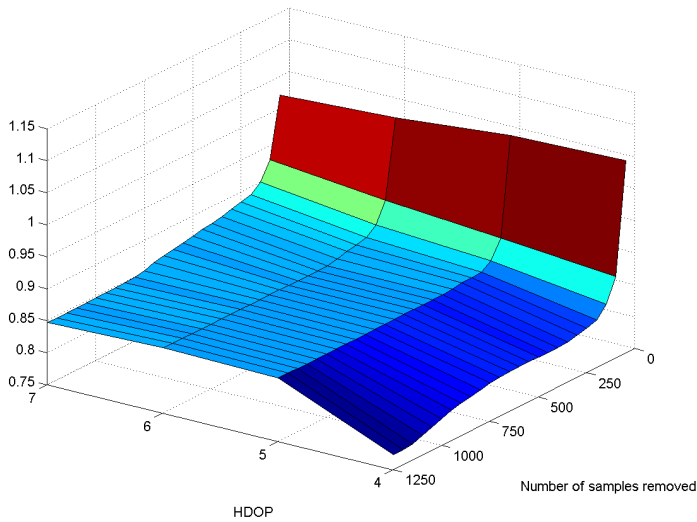


Figure 5.16. Standard deviation improvement by removing samples for which HDOP exceeds given the level (Lundby 2).

performance differential GPS (with combined INS-system) was performed. The DGPS receiver was a single antenna system with a standard deviation of 2 cm. The measurements took place at Hällered and lasted for approximately 5 days. See Appendix G and Appendix H for specification of the equipment used. The DGPS/INS unit was mounted in an estate car with the antenna placed on the roof of the car. The car was placed in a stationary position with a clear sky and southern view. The position sample rate was set to 10 Hz. The position data is presented in Figure 5.17. The position of the stationary measurement was drifting from the static position. Our measurements show a standard deviation of approximately 3.2 cm, which is larger than the specified 2 cm. The increase in standard deviation is negligible due to the limited number of tests. The IMU in the DGPS receiver should be connected with a fifth wheel to reduce some of the drift in the position (see Figure 5.18). During the test performed for this thesis, a fifth wheel was not available. Despite the advanced equipment, the system was still drifting from the position, up to 23.5 m from the static position. This distance is a worst case scenario. The plot of position (Figure 5.17) clearly shows that it makes five different deviations from its static position. The HDOP signal was not logged during this test, why the comparison between the drift and the HDOP signal was not possible.

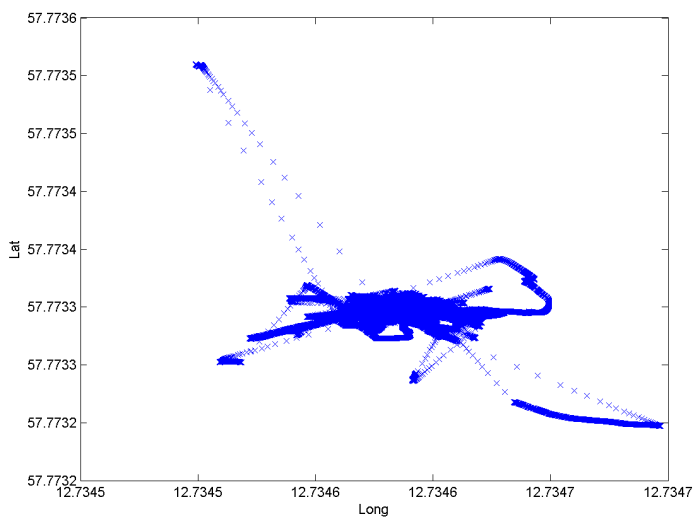


Figure 5.17. Stationary DGPS position measurements at Hällered



Figure 5.18. Fifth Wheel for vehicle testing [27]

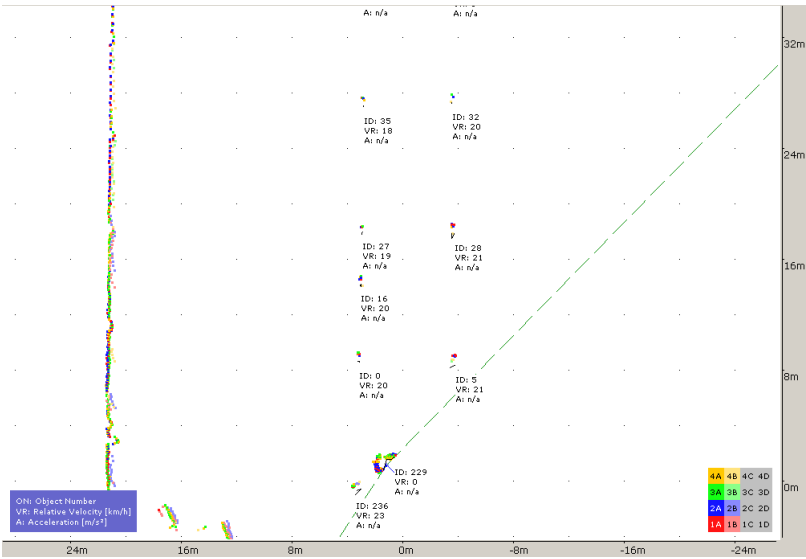


Figure 5.19. Plotted lidar detection from the Volvo Integrated Safety Truck driving at Lindholmen.

5.2 Laser Scanner Data Collection

Due to restricted availability to a lidar system, we were not able to perform these measurements by ourselves. The data sequences which we have studied are from the Volvo Integrated Safety Truck (VIST) at Volvo Technology. The data presented in Figure 5.19 is from a single, dual echo, four-layer technology laser scanner mounted on the truck's front left corner (see Appendix C.4.2 for more information). The angle of view is approximately 200° (dashed line in Figure 5.19). The figure clearly shows the objects in the nearby area of the truck. In this particular case it is an avenue with planted trees on both sides of the roadway. The left side of the picture shows a wall. The conclusions of this data collection is that the lidar is able to clearly detect and use the trees on the avenue as markings for e.g. positioning. This points to the possibilities of using static known objects for determining present position. In the picture some "objects", very near the front, are occurring. This is dirt that are stuck on the laserscanner. This dirt can be handled by filtering the signal.

Table 5.4. The DGPS accuracy

	Latitude	Longitude
Drift	23.5m	7m
σ	3.2cm	3.1cm

5.3 WLAN coverage

The distance coverage of a WLAN system is often specified by the manufacturers. The problem of these specifications is that the system is not applied in an environment that is similar to a test track. In order to verify the capacity of the WLAN system and get an indication of realistic working operating distances we did several measurements at Hällered test site.

5.3.1 WLAN range

To verify the WLAN range, we mounted a WLAN Access Point (AP) (see Appendix I for technical specifications of the equipment) to an omni-directional antenna (see Appendix J for technical specifications of the equipment). The antenna was mounted to a 3 m high pole to get good transference conditions (see Figure 5.20). The AP was connected to a laptop that constantly sent UDP messages at a constant transfer rate. The receiving unit was mounted in an estate car with an external antenna placed on the top center of the roof of the car. We drove the car towards the AP to see at what maximum distance we could obtain a connection.



Figure 5.20. WLAN test base station.

During the test, the weather conditions were very moist and sometimes rainy. These conditions were unfavourable for good WLAN coverage, although not a worst case weather scenario. We also performed the test at different vehicle speeds

to investigate if the connection was dependent on the speed.

Distance test

To determine the maximum distance at which coverage communication could be obtained, we drove against the antenna on a straight line and measured the distance with the odometer of the car. The first test speed was approximately 60 km/h and the distance from the AP was measured to approximately 600 m. When the speed was reduced to approximately 30 km/h the distance was measured to approximately 650 m when connection was established. During these tests the tendencies of latency were less than 5 ms independent of the vehicle speed. The tests were performed with constant visual contact with the AP.

Transfer Rate

During the tests a constant transfer rate was applied. The transfer rates that we tested were 1, 2, and 11 Mbit/s. The distances of the AP range were near constant for all tested transfer rates. In Section 4.2, the VSM is calculated to be less than 50 Bytes, with header and checksum included. With a realistic usage of 50 percent of the channel, the number of VSM's that the system will be able to send are presented in Table 5.5. With an update frequency of the VSM of 2 times per second and vehicle, the system will be able to handle at least 625 vehicles (calculated with the slowest transfer rate). A realistic assumption is that the number of vehicles at the test site will be less than 100, which leaves room for additional data transfer (e.g. measurement data).

Table 5.5. Messages per second

Transfer rate	50 % usage	Number of messages
1 Mbit/s	0.5 Mbit/s	1250
2 Mbit/s	1 Mbit/s	2500
11 Mbit/s	5.5 Mbit/s	13750

Environment

To see how the environment effects the connection possibilities, we drove around the curve endurance track to see if we had similar coverage as in the distance test. The curvature test results were not as good as the results of the straight line test. When the test vehicle lost visual contact, the coverage distance rapidly decreased.

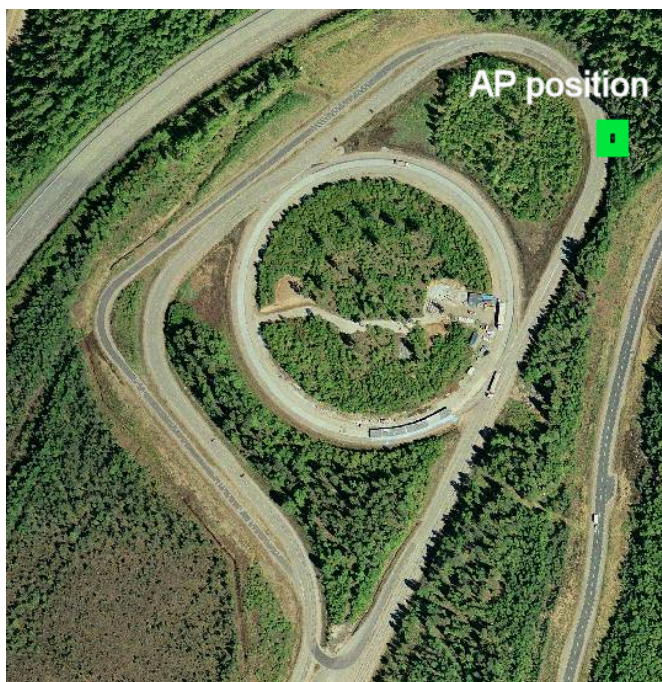


Figure 5.21. AP position at Hällered endurance track during WLAN distance test.

Chapter 6

Conclusions

This chapter summarizes all systems and techniques which are mentioned in the previous chapters. The advantages and disadvantages will be called to attention. Systems and techniques which are suitable for autonomous implementation will be presented and can be seen as a recommendation for implementation or for future investigations.

6.1 Positioning Conclusions

The positioning system is divided into two different parts, satellite positioning and vision. These two systems are intended to be integrated by sensor fusion to increase the performance and reliability of the complete system.

6.1.1 Positioning

To be able to drive autonomously, a positioning system is needed. This system needs to be robust, precise, and redundant.

DGPS

A local area DGPS solution is the technique that offers the most advantages. The possibility to increase the accuracy of more vehicles simultaneously is of great advantage. The GPS coverage, in this case at Hällered, is satisfying (see section 5.1.1), thus a GPS positioning device would be suitable.

To make sure that the vehicle stays within one lane of the roadway, the accuracy has to be less than one meter. To obtain the desired performance, a Differential GPS (DGPS) with a carrier-phase technology (CDGPS) has to be used. The accuracy of an CDGPS L1 receiver fulfills the demands of accuracy if the update frequency is proportional to the vehicle speed. When driving with a speed of up to 15 m/s, the update frequency has to be at least 20 Hz. When driving at high speeds, a faster update frequency is needed. This can be achieved with more sophisticated systems or in combination with INS systems.

Dilution of Precision

The GPS signal is very sensitive to the Geometric Dilution Of Precision (GDOP). The test which has been done (see Section 5.1.3) shows that the accuracy can be increased by isolating the time when the GDOP signal is high. Due to the orbits of the satellites, the GDOP can easily be predicted and the reliability of the position can be increased.

6.1.2 Vision

To obtain satisfactory robustness of an autonomous vehicle's position, the use of a vision system is needed. A good vision system is able to locate the position by itself if the surrounding environment is known (lane marks, guidepoles, etc). To obtain this feature a high resolution picture of the surrounding environment is needed.

Lidar

The vehicle vision unit with most advantages for this application is a lidar system. It provides a high resolution image with distances and bearing to objects and obstacles. The lidar needs a multi echo feature to be able to reduce unwanted detection (rain, fog, etc.) and a multi layer scanning to increase the resolution.

6.2 Communication Conclusions

The communication system needs to be robust with sufficient capacity to handle all communication. It must be fast enough to reduce the risk of latencies in the system.

6.2.1 WLAN

The WLAN technique is suitable for this implementation. The WLAN technique is known as an "off the shelf technology". The great advantages of this is that the technique is very cost efficient, and it still is under development with new standards for future use, e.g. IEEE 802.11n. The test result when using a WLAN shows that a significant distance can be covered with an omni-directional antenna. However, there is a performance problem when the vegetation blocks the line of sight between the AP and the receiving unit. To evade this problem, more AP's are needed to cover the complete area.

The Vehicle States Messages (VSM) size is very small compare to the transfer rate. This indicates that the WLAN technique is suitable for future improvement e.g. transferring the measurement data with the spared bandwidth.

6.3 Surveillance Conclusions

Surveillance of all vehicles can be accomplished by using the VSM:s. The vehicles' positions can be presented in real-time on a digital map. All additional information in the VSM can also be presented as additional information about the vehicles. With the VSM the current and predicted positions of the vehicles can be presented to the traffic controller.

6.4 Collision Avoidance Conclusions

The suggested collision avoidance system is based on prediction of the future trajectory of the vehicle. This feature can be obtained by using a vehicle model and with the information in the Vehicle States Message (VSM). A proposed VSM is presented in Section 4.2. The prediction of any future trajectory conflict decreases the possibilities of collisions.

To detect unpredicted objects a vision unit is needed. The lidar vision unit supplies the system with a high detailed image and a large field of view to detect objects in the nearby area.

These systems offer two different kinds of collision warnings. The warnings can be presented to an autonomous vehicle as well as a warning to a human driver. With these two systems, collision avoidance actions can be taken.

6.5 System Movability Conclusions

The recommended systems are movable because all of the systems are independent of location. The positioning system is based on satellite navigation and a vision unit which is integrated in the vehicle. The surrounding equipment such as the differential base station and the WLAN AP's can be placed on any desired test area. If the test area is large or the topography causes communication losses in some areas, more AP's can be added to resolve this problem. The collision avoidance system is independent of location because the trajectory conflict is calculated from the vehicle states and not based on a planned route conflict.

6.6 Future Work

This thesis work is based on literature and small scale testing. Many of the recommended systems are not tested by us in this thesis work. To verify the accuracy, capacity, and adequacy under realistic conditions, further tests needs to be done.

6.6.1 Positioning System

In Measurement and Data Collection (Chapter 5) the maximum drift of the position is very large. It seems to be a correlation between the HDOP signal and the position drift. As described in the chapter a simple filtering of the position was made which increased the accuracy with approximately ten percent. By doing

more studies of the GDOP signals (HDOP, VDOP, PDOP and TDOP) and the positioning drift, it might be possible to increase the position accuracy. The uncertainty of the position can be decreased if the GDOP signal is weighted and combined with additional sensors (e.g. IMU). Only a few tests with high performance equipment has been done within this thesis work, and some of the conclusions are based on low accuracy equipment and need to be verified using recommended equipment.

6.6.2 Lidar System

The specifications of the lidar system is not yet validated to the testing environment of the test track (influence of vibrations, bad weather conditions, etc).

6.6.3 Communication System

The implementation, testing, and validation for the Dual Antenna system and Neighbour Graph has not been done within this thesis.

Dual Antenna

To reduce the handover time when changing between AP's we recommend a dual antenna solution. The implementation of this technique should be done and verified.

Neighbour Graph

The neighbour graph technique might not be needed if the system is permanently installed but it will make the system more adaptive to changes and disturbances and make the system more movable due to the self building NG.

6.6.4 Collision Avoidance System

In this thesis work we have not investigated how the avoidance manoeuvre should be performed. This manoeuvre must be made in several different ways according to different traffic situations (e.g. unknown object on the road, future trajectory conflict, etc).

6.6.5 Fault Detection

In an autonomous vehicle the fault detection system must be extended. A human driver can detect malfunctions in the vehicle which are not indicated by sensors e.g. flat tire, drive shaft brake down, fire etc. To obtain this information more sensors might be needed along with analysis of e.g. CAN data. Descriptions of many of these errors and malfunctions can be gathered from interviewing the test drivers about their experiences.

Bibliography

- [1] Garmin 35/36 TracPak, *GPS Smart Antenna, Technical Specification*.
- [2] CNS Systems AB. Vdl mode 4, 2007. URL: http://www.cns.se/aviation/core.php?page=aviation_technology_vdl_mode4.
- [3] Neil Ackroyd and Robert Lorimer. *Global Navigation. A GPS User's Guide*. Lloyd's of London Press Ltd, 2 edition, 1994.
- [4] Fraport AG. Tacsys/caps fraport project, 2007. URL: <http://www.fraport.com/cms/company/dok/81/81480.tacsyscaps.htm>.
- [5] SICK AG. Homepage, 2007. URL: <http://www.sick.com/home/en.html>.
- [6] The Defense Advanced Research Projects Agency. D.a.r.p.a challange, 2007. URL: <http://www.darpa.mil/grandchallenge/index.asp>.
- [7] The Defense Advanced Research Projects Agency. D.a.r.p.a home, November 2007. URL: <http://www.darpa.mil>.
- [8] ZigBee Alliance. Zigbee alliance, 2007. URL: <http://www.zigbee.org>.
- [9] David Andersson and Johan Fjellström. *Vehicle Positioning with Map Matching Using Integration of a Dead Reckoning System and GPS*. Master's thesis, Linköpings Universitet, ISY, Linköpings Universitet, 581 83 Linköping, 2004. LiTH-ISY-EX-3457-2004.
- [10] Dave Bagby, Bob O'Hara, and Dave Roberts. Proposed revisions to the mac frame formats to support wireless distribution systems. *Document 802.11-94/248*, 1994.
- [11] Yaakov Bar-Shalom and William Dale Blair. *Multitarge-Multisensor Tracking: Applications and Advances Volume III*. Artech House, Inc., 2000.
- [12] Yaakov Bar-Shalom, X. Rong Li, and Thiagalingam Kirubarajan. *Estimation with Applications to Tracking and Navigation*. John Wiley & Sons, Inc., 2001.

- [13] Alberto Broggi, Stefano Cattani, Pier Paolo Porta, and Zani Paolo. A laserscanner-vision fusion system implemented on the terramax autonomous vehicle. *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference*, pages 111 – 116.
- [14] Jin Chen, Stefan Deutschule, and Kay Fuerstenberg. Evaluation methods and results of the intersafe intersection assistants. *Intelligent Vehicles Symposium, 2007 IEEE*.
- [15] Yin-Jun Chen, Ching-Chung Chen, Shou-Nian Wang, Han-En Lin, and Hsu Roy C. Gpsensecar -a collision avoidance support system using real-time gps data in a mobile vehicular network. *Systems and Networks Communication, 2006. ICSNC '06. International Conference*.
- [16] Dale DePries. Nmea data, 2007. URL: <http://www.gpsinformation.org/dale/nmea.htm>.
- [17] Andreas Eidehall. *Tracking and threat assessment for automotive collision avoidance*. Phd thesis, Linköpings Universitet, Department of Electrical Engineering, Linköpings Universitet, 581 83 Linköping, 2007.
- [18] Matts Eriksson and Jonas Lundmark. *Tecnical Verification and Validation of ADS-B/VDL Mode 4 for A-SMGCS*. Master's thesis, Linköpings Universitet, Department of Science and Technology, Linköpings Universitet, 601 74 Norrköping, 2002. LiTH-ITN-KTS-EX-02/34-SE.
- [19] ESA. European space agency: Egnos, 2007. URL: http://www.esa.int/esaNA/GGG63950NDC_egnosc_0.html.
- [20] Andreas Ewald and Volker Willhoeft. Laser scanners for obstacle detection in automotive applications. *Intelligent Vehicles Symposium, 2000. IV 2000. Proceedings of the IEEE*, pages 682 – 687.
- [21] FAA. Federal aviation administration : Waas, 2007. URL: http://www.faa.gov/airports_airtraffic/technology/waas/.
- [22] Jay Farrell and Matthew Barth. *The Global Positioning System & Inertial Navigation*. The McGraw-Hill Companies, Inc., 1998.
- [23] Daniel Fredriksson and Anders Schweitz. *Tecnical Verification and Validation of TIS-B using VDL Mode 4*. Master's thesis, Linköpings Universitet, Department of Science and Technology, Linköpings Universitet, 601 74 Norrköping, 2004. LiTH-ITN-KTS-EX-04/013-SE.
- [24] Kay Ch. Fuerstenberg, Klaus C.J. Dietmayer, and Volker Willhoeft. Pedestrian recognition in urban traffic using a vehicle based multilayer laserscanner. *Intelligent Vehicle Symposium, 2002. IEEE*, 1:31 – 35.
- [25] Bin Gao and Benjamin Coifman. Vehicle identification and gps error detection from a lidar equipped probe vehicle. *Intelligent Transportation Systems, 2006. Proceedings. 2006 IEEE*, pages 1537 – 1542.

- [26] Ibeo Automobile Sensor GmbH. Homepage, 2007. URL: <http://www.ibeo-as.com/english/default.asp>.
- [27] PEGASEM Messtechnik GmbH. Pegasem wheel, 2007. URL: http://www.pegasem.de/english/mainframe_uk.htm.
- [28] Mohinder S. Grewal, Lawrence R. Weill, and Andrews Angus P. *Global Positioning Systems, Inertial Navigation, and Integration*. John Wiley and Sons, Inc, 2001.
- [29] Fredrik Gustafsson, Lennart Ljung, and Mille Millnert. *Signalbehandling*. 2001.
- [30] Bernhard Hofmann-Wellenhof and Herbert Lichtenegger. *GPS Theory and Practice*. 5 edition, 2001.
- [31] Jonas Jansson. *Collision Avoidance Theory with Application to Automotive Collision Mitigation*. Phd thesis, Linköpings Universitet, ISY, Linköpings Universitet, 581 83 Linköping, 2005.
- [32] Christopher Jekeli. *Inertial Navigation Systems with Geodetic Applications*. Walter de Gynter GmbH & Co. KG, 2001.
- [33] Anders Johansson. *Kommuniaktionsgränssnitt mot GP&C transponder*. Master's thesis, Linköpings Universitet, Department of Science and Technology, Linköpings Universitet, 601 74 Norrköping, 2003. LiTH-ITN-EX-03/005-SE.
- [34] Rickard Karlsson. *Simulation Based Methods for Target Tracking*. Lic thesis, Linköpings Universitet, ISY, Linköpings Universitet, 581 83 Linköping, 2002.
- [35] Jörg Kibbel, Winfried Justus, and Kay Fürstenberg. Lane estimation and departure warning using multilayer laserscanner. *Intelligent Transportation Systems, 2005. Proceedings. 2005 IEEE*, pages 607 – 611.
- [36] Hye-Soo Kim, Sang-Hee Park, Chun-Su Park, Jae-Won Kim, and Sung-Jea Ko. Selective channel scanning for fast handoff in wireless lan using neighbor graph. July. The 2004 International Technical Conference on Circuits/Systems, Computer and Communications (ITC-CSCC2004), Japan.
- [37] Alexander Kirchner and Christian Ameling. Integrated obstacle and road tracking using a laser scanner. *Intelligent Vehicles Symposium, 2000. IV 2000. Proceedings of the IEEE*, pages 675 – 681.
- [38] Joo-Chul Lee and Dominik Kaspar. Pmip6 fast handover for pmip6 based on 802.11 networks. Technical report, ETRI, 161 Gajeong-dong Yuseong-gu Daejeon, 305-700 Korea, July 2007. URL: <http://tools.ietf.org/id/draft-lee-netlmm-fmip-00.txt>.
- [39] Oxford Technical Solutions Limited. Oxford technical solutions rt4000, 2007. URL: <http://www.oxts.co.uk/default.asp?pageRef=63>.

- [40] Arunesh Mishra, Min-ho Shin, and William A. Arbaugh. Context caching using neighbor graphs for fast handoffs in a wireless network. *INFOCOM 2004. Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies*, 1:361–365, 2004.
- [41] Arunesh Mishra, Min-ho Shin, and William A. Arbaugh. Improving the latency of 802.11 hand-offs using neighbor graphs. *International Conference On Mobile Systems, Applications And Services*, pages 70 – 83, 2004.
- [42] Novatel. Novatel gps, 2007. URL: <http://www.novatel.com/Documents/Papers/ProPakV3.pdf>.
- [43] Takashi Ogawa and Kiyokazu Takagi. Road environment recognition using on-vehicle lidar. *Intelligent Vehicles Symposium, 2006 IEEE*, pages 120 – 125.
- [44] Toshiya Okabe, Takayuki Shizuno, and Tsutomu Kitamura. Wireless lan network system for moving vehicles. *IEEE Symposium on Computers And Communications (ISCC 2005)*, (10):211 – 216.
- [45] Omnistar. Omnistar, 2007. URL: <http://www.omnistar.nl/DesktopDefault.aspx?tabid=344>.
- [46] Jörgen Ott and Dirk Kutscher. Drive-thru internet: IEEE 802.11b for "automobile" users. *IEEE Infocom 2004 Conference*.
- [47] Oxford Technical Solutions Limited, Oxford Technical Solutions Limited, 77 Heyford Park Upper Heyford, Oxfordshire OX25 5HD. *RT3000 Inertial and GPS Measurement System User Manual*, revision: 060502 edition.
- [48] Bradford W Parkinson and James J Spilker Jr. *Global Positioning System: Theory and Applications Volume II*. American Institute of Aeronautics and Astronautics Inc., 1996.
- [49] California PATH. Path, california partners for advanced transit and highways, 2007. URL: <http://www.path.berkeley.edu/>.
- [50] Jon Person. Writing your own gps applications: Part 2 - causes of precision error, 2007. URL: <http://www.developerfusion.co.uk/show/4652/2/>.
- [51] Martin Pettersson. *Distributed integrity monitoring of differential GPS corrections*. Master's thesis, Linköpings Universitet, ISY, Linköpings Universitet, 581 83 Linköping, 1998. LiTH-ISY-EX-2021.
- [52] Andreas Rönnebjerg. *A Tracking and Collision Warning System for Maritime Applications*. Master's thesis, Linköpings Universitet, ISY, Linköpings Universitet, 581 83 Linköping, 2005. LiTH-ISY-EX-05/3709-SE.
- [53] Sangho Shin, Andrea G. Forte, Anshuman Sing Rawat, and Henning Schulzrinne. Reducing mac layer handoff latency in IEEE 802.11 wireless lans. 2004. ACM 1-58113-920-9/04/0010.

- [54] Jan Sparbert, Klaus Dietmayer, and Daniel Streller. Lane detection and street type classification using laser range images. *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE*.
- [55] Carsten Spichalsky. Golf gti 53⁺ - the driverless car. *dSpace News*, (1):18–19, 2007.
- [56] Swepos. Swepos : Glonass, November 2007. URL: <http://swepos.lmv.lm.se/gps/glonass/glonass.htm>.
- [57] Swepos. Swepos produkter, 2007. URL: http://swepos.lmv.lm.se/index_prod.htm.
- [58] Kiyokazu Takagi, Katsuhiro Moirikawa, Takashi Ogawa, and Makoto Saburi. Lane recognition using on-vehicle lidar. *Intelligent Vehicles Symposium, 2006 IEEE*, pages 540 – 545.
- [59] Han-Shue Tan and Jihua Huang. Dgps-based vehicle-to-vehicle cooperative collision warning: Engineering feasibility viewpoints. *IEEE Transactions on intelligent transportation system (Vol.7 No.4 December 2006)*, (7), 2006. 1524-9050.
- [60] Han-Shue Tan and Jihua Huang. A low-order dgps-based vehicle positioning system under urban enviroment. *IEEE/ASME Transactions on mechatronics (Vol.11 No.5 October 2006)*, (5), 2006. 1083-4435.
- [61] Andrews Space & Technology. Glonass, November 2007. URL: http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml.
- [62] S. Wender, T Weiss, and K. Dietmayer. Improved object classification of laserscanner measurements at intersections using precise high level maps. *Intelligent Transportation Systems, 2006. Proceedings. 2006 IEEE*, pages 756 – 761.
- [63] Yilin Xhao. *Vehicle Location and Navigation Systems*. Artech House, INC., 1997.
- [64] Tomas Zirn. Wimax öppnar ny väg in till bredbandskunderna, 2007. URL: <http://computersweden.idg.se/2.2683/1.112141>.

Appendix A

Satellite Navigation

Satellite navigation technology is based on measuring the distance to different satellites. With the information of the satellite position and distance, the user position can be calculated by triangulation. Today only one system is fully operative, and it is the NAVSTAR GPS.

A.1 History

The first satellite navigation system was the Navy Navigation Satellite System (NAVSAT), also called TRANSIT. The system was using six low-orbiting (1100 km) satellites. The position was calculated by measuring the change in frequency of the satellites transmission as it speeds past in low orbit. Because the system only had six satellites the average time between the position update was about 90 min. The position accuracy was about 250 meter [3, 30].

A.2 GPS

The term GPS includes both the American system NAVSTAR (**N**avigation **S**atellite **T**iming **A**nd **R**anging **G**lobal **P**ositioning **S**ystem) and the Russian system GLONASS (**G**lobal **N**avigation **S**atellite **S**ystem) [3, 30].

NAVSTAR GPS

The GPS system is developed by the US DoD (United States Department of Defense). The NAVSTAR GPS is divided into tree parts: the space segment, the control segment and the user segment.

Space Segment

The space segment consists of 24 satellites arranged in 6 orbitals. The orbital planes have an inclination angle of 55 degrees relative the earth equator. The satellites have an average orbital altitude of approximately 20 200 km and i takes

Table A.1. Location of the Components of the Operation Control Segment

Master control station	Falcon Air Force Base, Colorado Springs, CO
Master control station (backup)	Gaithersburg, MD
Monitor station	Falcon Air Force Base, Colorado Springs, CO
Remote monitor station	Cape Canaveral, FL
Remote monitor station	Hawaii
Remote monitor station	Ascension Island
Remote monitor station	Diego Garcia
Remote monitor station	Kwajalein
Ground antenna	Cape Canaveral, FL
Ground antenna	Ascension Island
Ground antenna	Diego Garcia
Ground antenna	Kwajalein

approximately 12 hours to complete one orbit. Each satellite have a precise atomic clock and sends out messages with the current position, current time and an identity number. The satellites transmit on two frequencies centered on 1575.42 MHz and 12227.60 MHz [3, 30].

Control segment

The control segment consists of six monitoring stations, four ground antennas and a master control station. In Table A.1 is the control segment stations listed. The control segment main purpose is to monitoring the health and status of the space segment [3, 30].

User segment

The user segment provides the user with position, velocity, precise timing etc. To provide this information the GPS receiver use an antenna and a receiver-processor. The receiver-processor measures and decodes the satellite transmission.

Various GPS receivers uses different types of protocols to present the information. Some of the most common protocols is NMEA 0183, the Garmin protocol, the SiRF protocol etc [3, 30].

Geometric Dilution Of Precision

The **Geometric Dilution Of Precision** (GDOP) describe the geometric strength of the satellite configuration. A high number of satellites does not always indicates that the position accuracy is high. To obtain an accurate positioning with GPS navigation, the satellites have to be separated from each other. The GDOP value is a measure of the error contributed by the geometric relationship of the satellites positions. When the satellite are close together, the geometry is said to be weak and the GDOP value is in this cases high. A low GDOP value represents a better GPS positional accuracy due to the wider angular separation between the satellites

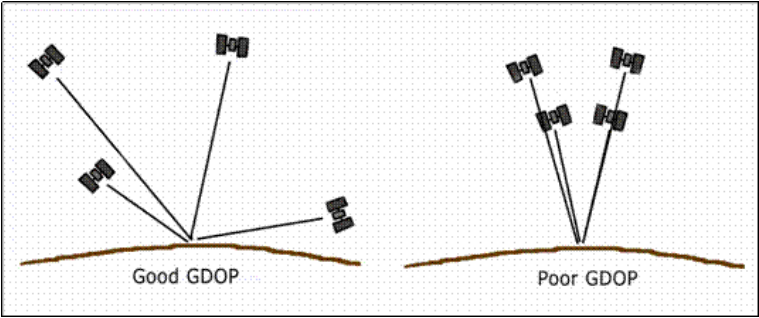


Figure A.1. Satellite constellation for good and poor Geometric Dilution Of Precision.

Table A.2. DOP value and rating

1	Ideal
2-3	Excellent
4-6	Good
7-8	Moderate
9-20	Fair
21-50	Poor

used to calculate a GPS units position (see Figure A.1). The ideal level is one, and up to six is acceptable. The DOP values and rating are presented in Table A.2.

The GDOP is divided into HDOP (Horizontal DOP), VDOP (Vertical DOP), PDOP (Position DOP, 3-D) and TDOP (Time DOP). These values are presented in different parts of the NMEA-code. These quantities follow mathematically from the positions of the usable satellites on the local sky [48].

NEMA 0183

The NMEA 0183 is a standard the are based on serial communication. It has one speaker and an optional number of receivers. It can be used by sonars, echo sounder, gyrocompass, autopilot, GPS receivers and many other types of instruments. The GPS system uses the standard and is sends a string of information (the most common are listed in Table A.3). One of the NMEA sentences is the GPGGA (GGA) sentence which is a essential fix data which provide 3D location and accuracy data. It includes information as the position (Latitude, Longitude), fix quality, number of satellites being tracked, horizontal dilution of position, altitude, mean sea level, time in seconds since last DGPS update, DGPS station ID number and a checksum data, see Table A.4 for example [16].

Table A.3. NMEA 0183

\$GPAAM	Waypoint Arrival Alarm
\$GPBOD	Bearing, Origin to Destination
\$GPBWW	Bearing, Waypoint to Waypoint
\$GPGGA	Global Positioning System Fix Data
\$GPGLL	Geographic Position, Latitude/Longitude
\$GPGSA	GPS DOP and Active Satellites
\$GPGST	GPS Pseudorange Noise Statistics
\$GPGSV	GPS Satellites in View
\$GPHDG	Heading, Deviation & Variation
\$GPHDT	Heading, True
\$GPRMB	Recommended Minimum Navigation Information
\$GPRMC	Recommended Minimum Specific GPS/TRANSIT Data
\$GPRTE	Routes
\$GPVTG	Track Made Good and Ground Speed
\$GPWCV	Waypoint Closure Velocity
\$GPWNC	Distance, Waypoint to Waypoint
\$GPWPL	Waypoint Location
\$GPXTE	Cross-Track Error, Measured
\$GPXTR	Cross-Track Error, Dead Reckoning
\$GPZDA	UTC Date/Time and Local Time Zone Offset
\$GPZFO	UTC and Time from Origin Waypoint
\$GPZTG	UTC and Time to Destination Waypoint

Table A.4. GGA Example

GGA - essential fix data which provide 3D location and accuracy data.

\$GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*47

Where	
GGA	Global Positioning System Fix Data
123519	Fix taken at 12:35:19 UTC
4807.038,N	Latitude 48 deg 07.038' N
01131.000,E	Longitude 11 deg 31.000' E
1	Fix quality
08	Number of satellites being tracked
0.9	Horizontal dilution of position
545.4,M	Altitude, Meters, above mean sea level
46.9,M	Height of geoid (mean sea level) above WGS84 ellipsoid
(empty field)	time in seconds since last DGPS update
(empty field)	DGPS station ID number
*47	the checksum data, always begins with *

GPS position determination

To calculate the position the GPS receiver needs to know the position of the satellites and the time a message have traveled from the satellite. In two dimensions the position $U(x, y, t)$ can be calculated according to Equation (A.1 - A.2) where n is the satellite number and R_n is the distance to satellite n . To get the right position in the two dimensional case it takes three satellites and in the general case four. The extra satellite is needed to synchronize the simple clock in the receiver with the precise atomic clock in the satellites. A larger number of satellites would provide better resolution (see Figure A.2 for an example) [28, 29, 51].

$$(S_{nx} - U_x)^2 + (S_{ny} - U_y)^2 = R_n^2 \quad (\text{A.1})$$

$$R_n = c \cdot \Delta t_n = c \cdot (t_n - t) \quad (\text{A.2})$$

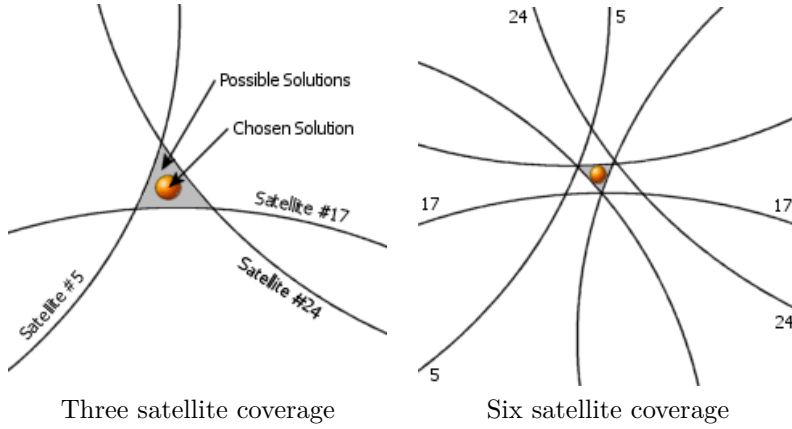


Figure A.2. Position accuracy according to the number of satellites. When more satellites are used in the position estimation, a higher accuracy can be achieved [50].

Accuracy

The GPS system is not exact in its position determination. There are several factors of disturbance that generates errors in the positioning. An included feature in the GPS system is Selected Availability (SA). This is a deliberately encoded random error that occurs and generates an error of about 100 m. This signal is now turned off and greater resolution is available to the general public.

The atmospheric conditions affect the speed of the GPS signals as they travel through the atmosphere and ionosphere. The error of this effect is minimal when the satellite is right above the receiver and the error effect increases when the satellite is nearer the horizon due to the signal is affected by this during a longer time. The ionospheric delay affects the speed of microwave signals differently based on frequency, the receiver is able to reduce this effect with comparing different

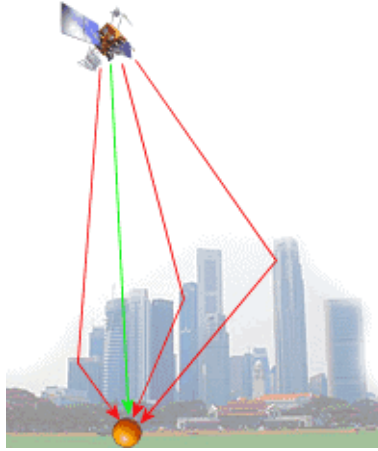


Figure A.3. Multipath example when the GPS signals are reflected on objects before reaching the user [50].

frequency bands, L1(1575,42 MHz) and L2 (1227,6 MHz). Ionospheric delay is a well-defined function of frequency and the total electron content (TEC) along the path, so measuring the arrival time difference between the frequencies determines TEC and thus the precise ionospheric delay at each frequency. This feature is mostly applied on expensive survey-grade receivers [28, 29, 51].

Multipath is also an effect that causes inaccuracy. The signals reflect and bounce off nearby objects and causes a difference in travel time (see Figure A.3). Multipath effects are less severe in moving vehicles. When the GPS antenna is moving, the false solutions using reflected signals quickly fail to converge and only the direct signals result in stable solutions. Clock errors is another factor of position error. The onboard clocks in the GPS satellites are extremely accurate, but they do suffer from some clock drift. This results in some inaccuracy of the position. All this faults summarize in an inaccuracy of approximately 15m [28, 29, 51].

GLONASS

GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) is the Russian version of the GPS system. The GLONASS system has its own satellites (18 satellites at this point). The project started in 1976. The goal of this project was to have global coverage by 1991 but has not reached this goal yet. The system rapidly fell into disrepair with the collapse of the Russian economy. In the end of 2009 the GLONASS system would have 24 satellites up and running for the wanted performance [56, 61].

Appendix B

Inertial Navigation Systems

Inertial navigation systems use an IMU (Inertial Measurement Unit). This is a closed system that detect movement and acceleration with a combination of accelerometers and angular rate sensors. The IMU detect the current acceleration and the rate of change in the angular sensors (pitch, roll and yaw, see Figure B.1) and sum these up to calculate the total change from the initial position. As a stand-alone system it suffer from accumulated errors [47]. All inertial navigation systems suffer from integration drift, as small errors in measurement are integrated in progressively larger errors in velocity an especially position. Additional roll error due to centripetal and Coriolis acceleration. The IMU is adding all detected changes to the current position and any error is accumulated. It can be based on several different techniques, e.g. gyro stabilized platforms (B.2) or strap down platforms. The platforms are based on vibrating structure gyroscopes (B.3), fiber optic gyros, ring laser gyros (B.4 (a)) and/or pendular accelerometers (B.4 (b)). All of these solutions have their benefits and disadvantages [9, 22, 32, 63].

B.1 Dead Reckoning

Dead Reckoning (DR) is a primitive technique to determine the position of a vehicle. If the starting position and all the previous displacement are known the position can be calculated through:

$$N(k+1) = N(k) + v(k)T \cos(\theta(k)) \cos(\psi(k)) \quad (\text{B.1})$$

$$E(k+1) = E(k) + v(k)T \cos(\theta(k)) \sin(\psi(k)) \quad (\text{B.2})$$

$$Z(k+1) = Z(k) + v(k)T \sin(\theta(k)) \quad (\text{B.3})$$

$$\psi(k+1) = \psi(k) + T\dot{\psi}(k) \quad (\text{B.4})$$

$$\theta(k+1) = \theta(k) + T\dot{\theta}(k) \quad (\text{B.5})$$

where T is the sample time and, N , E and Z are the north, east and height position coordinates. v is the velocity, ψ is the yaw angle, and θ is the pitch angle. All the signals are supposed to be constant during one sample period [9, 22, 32, 63].

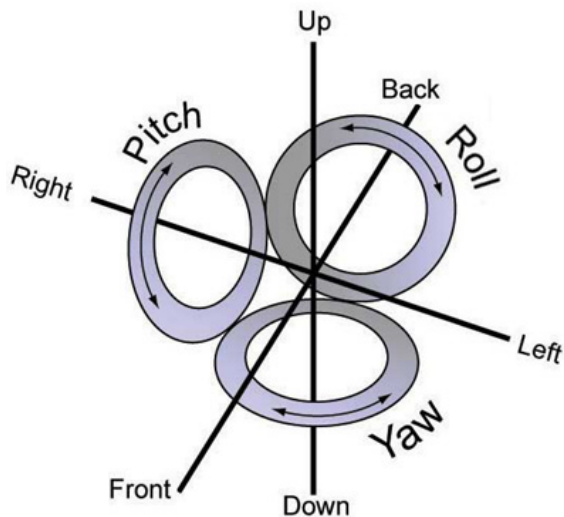


Figure B.1. Roll, pitch and yaw angles.

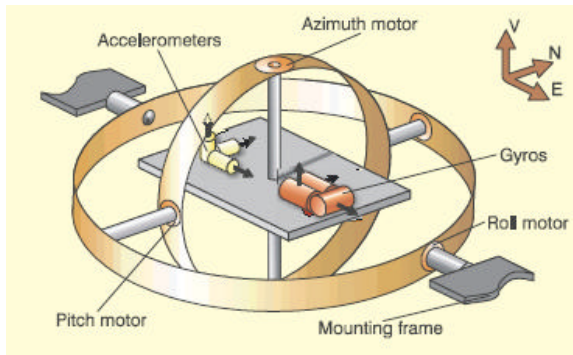


Figure B.2. Gimbaled Gyro stabilized platform.

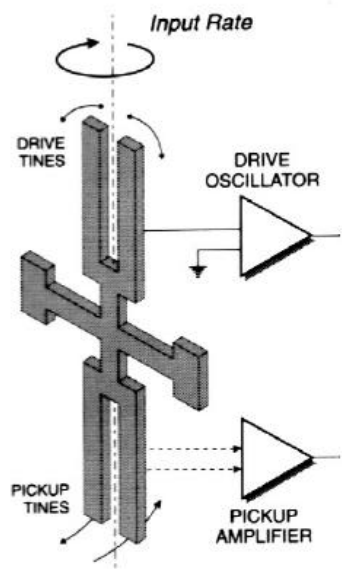
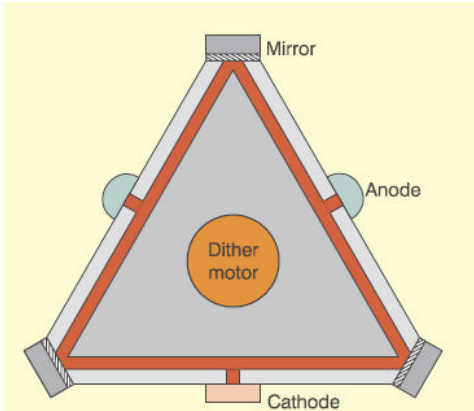
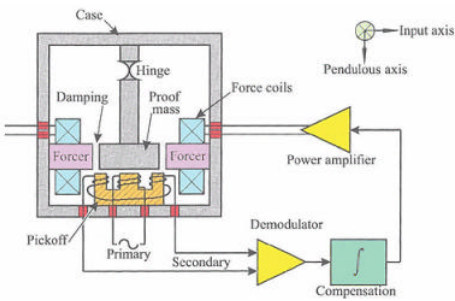


Figure B.3. Vibrating structure gyroscope.



a
Ring laser gyro



b
Pendular accelerometers

Figure B.4. Inertial gyro systems

Appendix C

Prototype Systems

The theory of driving vehicles autonomous is already implemented by different car manufacturers.

C.1 PATH

An example of line follower is the American PATH project. The ambition of this project is to have autonomous traffic on the highways in California. The technique that being used is a magnetic trail that are built in the road. By putting magnets in the road (sizes of a marker pen) placed with distances of approximately 1-1.2m the vehicle can follow the magnetic line. Using the magnetic domains of the permanent magnets, the system is able to use them as an ID-tag. The vehicles are able to sense the field strength and by this it can control the direction and speed of the vehicle. This technique gives a longitudinal accuracy of less then 0.3m and lateral less then 0.05m. Five magnetometers is placed beneath the vehicle, and by signal processing the vehicle is able to determine its position. Due to the simple path, the implementation is quite robust and can handle high speed driving. The implementation of this system demands high effort in setting up the road with magnets. Although the permanent magnets are at low cost but the path is very static and variation of driving schedules are minimal [49].

C.2 VW Golf GTi 53⁺¹

Volkswagen AG has made a prototype car called "Golf GTi 53⁺¹". It is a fully autonomous car that uses a laser scanner and a DGPS for navigation. The basic use of this car is handling and brake tests due to its capability of precision driving. By using the autonomous car, the repeating sequences is much more like an exact duplicate then with a human driver.

The Golf GTi uses an Ibeo laser scanner mounted below the front license plate for front vision. For positioning and navigation it uses a DGPS system, RT3002 from Oxford Technical Solutions. This is a combination system that are using

a DGPS beacon antenna and an inertial navigation system to obtain a very high position update frequency. This sophisticated equipment supplies the car the exact position in sub dm level (less then 2.5 cm). The track is limited by cones that easily can be detected by the laser scanner. By using the vision of the car on a scouting lap, the car stores the route of the track to compute the optimal driving schedule. A MicroAutoBox from dSPACE is implemented to control the power steering, brake booster and the accelerator pedal [55].

C.3 Team LUX

The Team LUX is Ibeo's and SICK's first D.A.R.P.A Grand Challenge team [6]. They are using a modified Volkswagen Passat and made it fully autonomous. The car navigates by a DGPS (Omnistar [45]) i combination with three laser scanners (Ibeo). The use of three laser scanners gives the car complete 360° vision around the vehicle. This application make it possible to get an exact position in combination with the DGPS without any INS systems. The use of the laser scanner vision, it calculates its position from reference points in the near area. This gives the system very little drift [5, 26].

C.4 Previous Volvo projects

C.4.1 LKAB

A previous project that has been implemented by AB Volvo is the autonomous trucks that runs i the mine industry at LKAB. The projects purpose was to build a number of trucks that was supposed to drive autonomous in a restricted area, it included active steering and modification in existing control units. The navigation was based on laser scanning. By placing reflectors in the specified route and using laser scanners for detection, the system was able to navigate by building a local reference network and keep the vehicle on a specified route.

C.4.2 VTEC Prototype truck

The Volvo Technology (VTEC) are working with a concept truck, the Volvo Integrated Safety Truck (VIST). This concept truck is equipped with several different observation technologies, main purpose of collision avoidance. One of this features are the lidar system. In Figure C.1, the VIST is shown and the circled area shows the lidar system integrated in the front of the truck. The lidar is used for collision avoidance and as a pre-crash system.



Figure C.1. The Volvo Integrated Safety Truck with lidar sensor implementation (circled).

Appendix D

Mathematics

D.1 Haversine Equation

The haversine function is given by Equation (D.1). By setting Equation (D.2) as the variable h , we can easily calculate the distance d between the points of interest.

$$\text{haversin}(\theta) = \sin^2\left(\frac{\theta}{2}\right) \quad (\text{D.1})$$

$$\text{haversin}\left(\frac{d}{R}\right) = \text{haversin}(\Delta\phi) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \text{haversine}(\Delta\lambda) \quad (\text{D.2})$$

$$d = R \cdot \text{haversin}^{-1}(h) = 2R \cdot \arcsin(\sqrt{h}) \quad (\text{D.3})$$

D.2 Covariance

$$\text{Cov}(X, Y) = E((X - \mu)(Y - \nu)) \quad (\text{D.4})$$

$$\rho_{X,Y} = \frac{\text{Cov}(X, Y)}{\sigma_X \sigma_Y} \quad (\text{D.5})$$

Appendix E

Kalman filter

E.1 Extended Kalman filter

The KF is made for a linear model. Many models are nonlinear function in either the state or measurement update. To use the KF the system can be linearized around the latest state estimation, when this is done the KF can be applied [12, 52].

Consider a system

$$x(t+1) = f(x(t)) + \omega(t) \quad (\text{E.1a})$$

$$y(t) = c(x(t)) + v(t) \quad (\text{E.1b})$$

where the function $f(x(t))$ and $h(x(t))$ represent nonlinear functions. To linearize the states a first order Taylor series around the current state are used. This will result in this approximation:

$$f(t) \approx f(\hat{x}(t|t)) + F(t) \cdot (x(t) - \hat{x}(t|t)) \quad (\text{E.2a})$$

$$c(t) \approx c(\hat{x}(t|t-1)) + C(t) \cdot (\hat{x}(t) - \hat{x}(t|t-1)) \quad (\text{E.2b})$$

where

$$F(t) = \left. \frac{\partial f(t)}{\partial x} \right|_{x=\hat{x}(t|t)} \quad (\text{E.3a})$$

$$C(t) = \left. \frac{\partial c(t)}{\partial x} \right|_{x=\hat{x}(t|t-1)} \quad (\text{E.3b})$$

With these approximations Equation (E.1a) and (E.1b) can be rewritten as:

$$\begin{aligned} x(t+1) &= F(t)x(t) + f(\hat{x}(t|t)) - F(t)\hat{x}(t|t) + \omega(t) \\ y(t) &= C(t)x(t) + c(\hat{x}(t|t-1)) - C(t)\hat{x}(t|t-1) \end{aligned}$$

The new state update and measurement update now looks like:

$$\begin{aligned}
 \hat{x}(t+1|t) &= F(t)\hat{x}(t|t) + (f(\hat{x}(t|t)) - F(t)\hat{x}(t|t)) = f(\hat{x}(t|t)) \\
 \hat{x}(t|t) &= \hat{x}(t|t-1) + K(t)(y(t) - h(\hat{x}(t|t-1) - C(t)\hat{x}(t|t-1)) - C(t)\hat{x}(t|t-1)) \\
 &= \hat{x}(t|t-1) + K(t)(y(t) - h(\hat{x}(t|t-1)))
 \end{aligned}$$

The EKF is summerized in Algorithm 3

Algorithm 3 Extended Kalman filter, EKF

Initial values:

$$\begin{aligned}
 \hat{x}(0|-1) &= x_0 \\
 P(0|-1) &= \Pi_0
 \end{aligned}$$

Time update:

$$\hat{x}(t+1|t) = f(\hat{x}(t|t)) \quad (\text{E.6a})$$

$$P(t+1|t) = F(t)P(t|t)(F(t))^T + Q_t \quad (\text{E.6b})$$

Filter gain computation:

$$L(t) = P(t|t-1)C(t)^T[C(t)P(t|t-1)C(t)^T + R_t]^{-1} \quad (\text{E.7})$$

Measurement update:

$$\hat{x}(t|t) = \hat{x}(t|t-1) + L(t)(y(t) - c(\hat{x}(t|t-1))) \quad (\text{E.8a})$$

$$P(t|t) = (I - L(t)C(t))P(t|t-1) \quad (\text{E.8b})$$

where

$$F(t) = \left. \frac{\partial f(t)}{\partial x} \right|_{x=\hat{x}(t|t)} \quad (\text{E.9a})$$

$$C(t) = \left. \frac{\partial c(t)}{\partial x} \right|_{x=\hat{x}(t|t-1)} \quad (\text{E.9b})$$

and

$$Q_t = \text{Cov}(w_t) \quad (\text{E.10a})$$

$$R_t = \text{Cov}(e_t) \quad (\text{E.10b})$$

Appendix F

Globalsat

PRODUCT SPECIFICATION

USB GPS RECEIVER

BU-353

Ver 1.03

GlobalSat Technology Corporation

16, No.186, Chien 1 Road, 235 Chung Ho City, Taipei Hsien, Taiwan ,R.O.C.

Tel: 886-2-8226-3799(Rep.)

Fax: 886-2-8226-3899

Web: www.globalsat.com.tw

E-mail: service@globalsat.com.tw

Product Feature

- "SiRF starIII" high performance and low power consumption chipset
- All-in-view 20-channel parallel processing
- Built-in patch antenna
- Very High sensitivity to satellite signal (Tracking Sensitivity:-159 dBm)
- Extremely fast TTFF(Time To First Fix) at low signal level
- Build-in SuperCap to reserve system data for rapid satellite acquisition.
- Supported NMEA 0183 data protocol
- Super-cohesive magnetic for mounting on the car
- Water resisted and non-slip on the bottom
- USB interface connection port
- LED indicator for GPS fix or not fix

LEDOFF:	Receiver switch off
LED ON:	No fixed, Signal searching
LED Flashing:	Position Fixed

System Specification

Electrical Characteristics (Receiver)	
Chipset	SIRF Star III
Frequency	L1, 1575.42 MHz
C/A Code	1.023 MHz chip rate
Channels	20 channel all-in-view tracking
Sensitivity	-159 dBm
Accuracy	
Position Horizontal	10m 2D RMS (SA off)
Velocity	0.1m/sec
Time	1 micro-second synchronized to GPS time
WAAS enabled	5m 2D RMS
Datum	
Datum	WGS-84
Acquisition Rate	
Hot start	1 sec., average (with ephemeris and almanac valid)
Warm start	38 sec., average (with almanac but not ephemeris)
Cold start	42 sec., average (neither almanac nor ephemeris)
Reacquisition	0.1 sec. average (interruption recovery time)
Protocol	
GPS Protocol	Default: NMEA 0183
GPS Output Data	SiRF binary >> position, velocity, altitude, status and control ; NMEA 0183 protocol.supports command: GGA, GSA, GSV, RMC, VTG, GLL (VTG and GLL are optional)
GPS transfer rate	Software command setting (Default : 4800,n,8,1 for NMEA)
Dynamic Condition	
Acceleration Limit	Less than 4g
Altitude Limit	18,000 meters (60,000 feet) max.
Velocity Limit	515 meters/sec. (1,000 knots) max.
Jerk Limit	20 m/sec**3
Temperature	
Operating	-40°~ 85°C
Storage	-40°~ 85°C
Humidity	Up to 95% non-condensing
Power	
Voltage	4.5V ~ 6.5V
Current	80mA typical
Physical Characteristics	
Dimension	53mm diameter , 19.2mm height
USB Cable Length	65"



USB GPS Receiver

Due to continuous product improvements, all specifications may be subject to change without notice

Appendix G

Oxford Tech RT 3002

RT3000

Inertial and GPS Measurement System

Features

- Export License Exempt
- 2cm Positioning
- 0.05km/h Velocity
- 10mm/s² Acceleration
- Lateral Acceleration
- 0.03° Roll, Pitch
- 0.15° Slip Angle
- 0.01°/s Angular Rates
- Other Measurements
- Real-Time
- Low Latency
- CAN Output
- Wheel speed input
- 500MB Logging
- 5 min Installation
- Compact Size

Vehicle Applications

- Vehicle dynamics
- Autonomous vehicles
- Roll-over testing
- Lane change
- NHTSA ESC
- ITS testing
- Simulation verification
- Acceleration/braking
- Lap timing, racing

Other Applications

- AHRS
- Video Correction
- Road Survey

Oxford Technical Solutions
77 Heyford Park
Upper Heyford
Oxfordshire
OX25 5HD
England
Tel: +44 1869 238 015
Fax: +44 1869 238 016
<http://www.oxts.co.uk>
<mailto:info@oxts.com>

RT3000 Inertial and GPS Navigation System

The RT3000 Inertial and GPS Navigation Systems are advanced six-axis inertial navigation systems, blended with precision GPS, to give robust outputs of position, orientation and velocity.

The RT3000 Inertial and GPS Navigation System includes three angular rate sensors (gyros), three servo-grade accelerometers, a GPS receiver and all the required processing in one very compact box.

Six single GPS antenna models in the RT3000 family allow us to offer very competitively priced products. The difference between the products is the positioning performance of the GPS receiver, with our most accurate model offering 2cm accuracy.

The RT3000 works as a stand-alone, autonomous unit and

requires no user input before it starts operating.

The outputs from the RT3000 Inertial and GPS Navigation System are derived from the measurements of the accelerometers and gyros. Using the inertial sensors for the main outputs gives the RT3000 system a high update rate (100Hz) and a wide bandwidth. All the

outputs are computed in real-time with a very low latency.

The RT3000 Inertial and GPS Navigation Systems outputs its real-time measurements over RS232, Ethernet and CAN bus.

The CAN bus output can be combined into a vehicle's CAN bus or captured using any CAN data acquisition system. The real-time nature allows the RT3000 to be used for *hardware in the loop* and controller development. Connection to powerful tools like dSPACE is easy. CAN DBC files are provided.

The precision ADC in the RT3000 gives more than 20 bits of resolution. The resolution of the acceleration measurements is 0.12mm/s² (12µg). The ADC oversamples the analogue sensors and uses coning/sculling motion compensation algorithms to avoid aliasing of the signals.

The internal processing includes the strapdown algorithms (using a WGS-84 earth model), Kalman filtering and in-flight alignment algorithms.



Vehicle Dynamics Testing



Autonomous Vehicles



Aerial Survey Applications

Parameter	RT3200	RT3100	RT3020	RT3002	RT3050	RT3040
Position Accuracy	3.0mCEP SPS	1.8mCEP SPS	1.8mCEP SPS	1.5mCEP SPS	1.8mCEP SPS	1.5mCEP SPS
	1.4mCEP SBAS	1.2mCEP SBAS	1.2mCEP SBAS	0.8mCEP SBAS	1.2mCEP SBAS	0.8mCEP SBAS
	1.0mCEP DGPS	0.4mCEP DGPS	0.2m 1 σ DGPS	0.02m 1 σ DGPS	0.5mCEP VBS ²	0.1mCEP HP ²
Velocity Accuracy	0.2 km/h RMS	0.1 km/h RMS	0.08km/h RMS	0.05km/h RMS	0.08km/h RMS	0.07km/h RMS
Acceleration						
– Bias	10 mm/s ² 1 σ	10 mm/s ² 1 σ	10 mm/s ² 1 σ	10 mm/s ² 1 σ	10 mm/s ² 1 σ	10 mm/s ² 1 σ
– Linearity	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
– Scale Factor	0.1% 1 σ	0.1% 1 σ	0.1% 1 σ	0.1% 1 σ	0.1% 1 σ	0.1% 1 σ
– Range ¹	100 m/s ²	100 m/s ²	100 m/s ²	100 m/s ²	100 m/s ²	100 m/s ²
Roll/Pitch	0.1° 1 σ	0.05° 1 σ	0.05° 1 σ	0.03° 1 σ	0.04° 1 σ	0.03° 1 σ
Heading	0.2° 1 σ	0.1° 1 σ	0.1° 1 σ	0.1° 1 σ	0.1° 1 σ	0.1° 1 σ
Angular Rate						
– In-run Bias	2 deg/hr	2 deg/hr	2 deg/hr	2 deg/hr	2 deg/hr	2 deg/hr
– ARW	0.2 deg/ $\sqrt{\text{hr}}$	0.2 deg/ $\sqrt{\text{hr}}$	0.2 deg/ $\sqrt{\text{hr}}$	0.2 deg/ $\sqrt{\text{hr}}$	0.2 deg/ $\sqrt{\text{hr}}$	0.2 deg/ $\sqrt{\text{hr}}$
– Range ¹	100°/s	100°/s	100°/s	100°/s	100°/s	100°/s
Track (at 50km/h)	0.2° RMS	0.1° RMS	0.07° RMS	0.1° RMS	0.1° RMS	0.08° RMS
Slip Angle (at 50km/h)	0.3° RMS	0.2° RMS	0.15° RMS	0.15° RMS	0.15° RMS	0.15° RMS
Lateral Velocity	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%
Update Rate	100 Hz	100 Hz	100 Hz	100 Hz	100 Hz	100 Hz
Calculation Latency	3.9 ms	3.9ms	3.9 ms	3.9 ms	3.9 ms	3.9 ms

Note 1. 300m/s² and 300°/s options are available. Note 2. A subscription is required to use OmniStar VBS and OmniStar HP Services.



Inertial Sensors in RT3000 include servo-grade accelerometers and precision MEMS angular rate sensors. Powerful 40MHz floating point DSP takes care of coning, sculling and aliasing.



Magnetic GPS antenna for vehicle mounting. Other types available.

The internal Pentium-class processor runs QNX real-time operating system to ensure that the outputs are always delivered on time.

The Kalman filter monitors the performance of the system and updates the measurements using GPS and wheel speed. By using the measurements from GPS, the RT3000 system is able to maintain highly accurate measurements and correct its inertial sensor errors.

The RT3000 comes with acquisition software that displays the data on a PC or on Pocket PC devices. The PC software can be used to save tests in files, display real-time results and monitor the performance.

The internal logging enables the RT3000 to work stand-alone. Post-mission, data can be output in ASCII text format and loaded in to the software of your choice.

Simple configuration software allows the user to change the mounting angle; displace the measurement point to a virtual location; change the differential GPS options, etc.

Models

To choose the best model for your application, think about the positioning accuracy you require and what differential GPS corrections you can supply. OmniStar systems give excellent results over a wide area. The RT3002 can give

more accurate positioning in a local area where licence-free radios can be used to transmit the corrections.

The RT3000 products are also available as dual antenna models. Where accurate heading in low dynamics is required, the dual-antenna model may be more suitable.

For further information please contact Oxford Technical Solutions or your nearest local agent.

Parameter	RT3000
Power	9-18 V d.c. 15W
Dimensions (mm)	234 x 120 x 80
Weight	2.2 kg
Operating Temperature	–10 to 50°C
Vibration	0.1 g ² /Hz 5-500 Hz
Shock Survival	100G, 11ms
Internal Storage	500 MB
Dual Antenna	No

Appendix H

Oxford Tech RT-Base

RT-Base

GPS Base Station

Features

- 45cm DGPS Corrections
- 20cm L1 Corrections
- 2cm L2 Corrections
- RTCA Format
- Integral 10h Battery
- Integral Charger
- Integral Mains PSU
- Integral Radio Modem
- 450MHz Band
- Error Correcting Transmission
- Save/Restore Antenna Position
- Multi-path Rejecting GPS Antenna
- IP65 Rated Case

Compatibility

- RT3000
- RT4000
- RTCA

Oxford Technical Solutions
77 Heyford Park
Upper Heyford
Oxfordshire
OX25 5HD
England

Tel: +44 1869 238 015
Fax: +44 1869 238 016
<http://www.oxts.co.uk>
<mailto:info@oxts.com>

RT-Base GPS Base Station



The RT-Base is a portable GPS Base Station capable of providing Differential Corrections for Differential GPS Receivers.

The RT-Base can be used with the RT3000 products to give up to 2cm positioning accuracy.

One RT-Base unit can be used to correct multiple DGPS systems. Additional Remote Radio Modems can be purchased for each mobile DGPS system.

Fast To Install

The RT-Base has been designed with installation speed in mind. Simply connect the GPS Antenna and the Radio Modem Aerial; then turn on.

The unit can start transmitting corrections in under 2 minutes with a known location or under 5 minutes if the position needs to be averaged.

Training for operators is also minimal. Instructions are printed on the inside of the RT-Base unit and a Quick

Guide is provided to make the operation easy.

Integral Battery

The RT-Base includes a 10 hour battery for all-day operation. A 12-volt input is provided for an external battery if required.

An internal mains charger can charge the RT-Base's battery in 2 hours. The internal power supply can be used to run the system if mains power is available.

Multipath Rejection

The RT-Base uses Pulse-Aperture Correlator Technology to minimise the effects of multipath.

The GPS-700 Pin-Wheel Technology Antenna includes a ground-plane to minimise ground surface multi-path and reflections.

Qty	RT-Base components with SATEL radio
1	RT-Base Unit
1	GPS-C006 15m GPS Antenna Cable
1	GPS-702-GG GPS Antenna
1	SATEL Satellite-3ASd Radio Modem
2	Radio Modem Aerial/Antenna with 3m cable
1	Lightweight Tripod
1	IEC Mains Cable
1	77C0002B Power Cable
1	Internal Radio Link – fit to use internal radio
1	RT-Base User Manual
1	RT-Base Quick Guide

Note 1: Different radios are required for operation in different countries

Parameter	RT-Base Specifications
Mains Power	110-240 V AC. 50-60Hz. 3A Max.
Battery	12V, 7Ah, Sealed Lead-Acid
Charge Time	2 hours
Operating Time	> 10 hours
Operating Temperature	0 to 50°C
Charge Temperature	10 to 40°C
Environment	IP65 – with lid closed
Relative Humidity	95%, non-condensing
Corrections	RTCA (Differential, L1, L2)
Frequency	1 Hz
Format	RS232
Dimensions	486 x 392 x 192 mm
Weight	12.6 kg



The RT-Base includes a Remote Radio Modem and Antenna for use on the vehicle. The Radio Modem in the RT-Base will be factory configured for use in a particular country or territory.



For correct operation of the RT-Base it is essential to locate the GPS antenna in a location where it has a full view of the sky, down to an elevation of 10 degrees in all directions. It must also be away from reflective objects, like buildings and trees.

Radio Modem

The RT-Base includes an internal radio modem. Several options are available so that the RT-Base can be used without a license in many countries.

Advanced Error Correcting Codes are used in the Radio Modem’s communication to enhance reliability and minimise the number of corrupt packets.

The Radio Modem provides reliable transmission over a 2km range in an open environment. Since some packets

can be dropped or have errors, the Radio Modem can be used up to a range of 5km in open environments.

IP65 Rugged Case

When the lid is closed the RT-Base has IP65 ingress protection, making it suitable for use in all weathers.

The RT-Base is mounted in a rugged ultra high impact PELI case.

For further information please contact Oxford Technical Solutions or your nearest local agent.

Radio	Details
SATEL	380 - 480 MHz band, up to 1 W, typically 5 km. License free bands available for many European countries. Radio will typically cover 8 bands with 25 kHz channel spacing.
SATEL	869 MHz band, up to 500 mW, typically 2 km. License free across most of European Union.
Freewave	900 MHz band, up to 1 W, typically >10 km. License free in USA, Brazil, Canada.
Futaba	2.4 GHz band, 10 mW, maximum 2 km. License free in Japan.

Appendix I

Cisco Aironet 1240G Series Access Point

Cisco Aironet 1240G Series Access Point

Cisco® Aironet® 1240G Series Access Points provide single-band 802.11g wireless connectivity for challenging RF environments such as factories, warehouses, and large retail establishments (Figure 1). Connectorized antennas, a rugged metal enclosure, and a broad operating temperature range offer extended range and coverage versatility. The Cisco Aironet 1240G Series provides local as well as inline power, including support for IEEE 802.3af Power over Ethernet (PoE).

Figure 1. Cisco Aironet 1240G Access Point



The Cisco Aironet 1240G Series is a component of the Cisco Unified Wireless Network, a comprehensive solution that delivers an integrated, end-to-end wired and wireless network. Using the radio and network management features of the Cisco Unified Wireless Network for simplified deployment, the Cisco Aironet 1240G Series extends the security, scalability, reliability, ease of deployment, and manageability available in wired networks to the wireless LAN (WLAN).

The Cisco Aironet 1240G Series is available in two versions: unified or autonomous. Unified access points operate with the Lightweight Access Point Protocol (LWAPP) and work in conjunction with Cisco wireless LAN controllers and the Cisco Wireless Control System (WCS). When configured with LWAPP, the Cisco Aironet 1240G Series can automatically detect the best-available Cisco wireless LAN controller and download appropriate policies and configuration information with no manual intervention. Autonomous access points are based on Cisco IOS® Software and can optionally operate with the CiscoWorks Wireless LAN Solution Engine (WLSE). Autonomous access points, along with the CiscoWorks WLSE, deliver a core set of features and can be field-upgraded to take full advantage of the benefits of the Cisco Unified Wireless Network as requirements evolve.

Applications

Designed for rugged environments and installations that require antenna versatility, the Cisco Aironet 1240G Series features antenna connectors for extended range or coverage versatility and more flexible installation options. Manufacturing applications, for example, can place WLANs in hazardous locations and remotely place antennas in those locations while securing the Cisco Aironet 1240G Series Access Points.

The metal housing and industrial-grade components of the Cisco Aironet 1240G Series provide the ruggedness and extended operating temperature range required in factories, warehouses, “big box” retail environments, and similar facilities. High transmit power, receive sensitivity, and delay spread for 2.4-GHz radios provide the long range and large coverage area consistent with these applications. Access points can be placed above ceilings or suspended ceilings, allowing antennas to be discreetly placed below drop ceilings. The UL 2043 rating of the Cisco Aironet 1240G Series allows for placement of the access points above ceilings in plenum areas regulated by municipal fire codes. Public access applications such as large hotel buildings can also present a challenging RF environment; the antenna versatility of the Cisco Aironet 1240G Series, together with industry-leading range and coverage, provides reliable performance for the most demanding environments.

Features and Benefits

Table 1 lists the features and benefits of Cisco Aironet 1240G Series Access Points.

Table 1. Features and Benefits of Cisco Aironet 1240G Series Access Points

Feature	Benefit
802.11g radios	The access points provide 54 Mbps of capacity and compatibility with older 802.11b clients.
Dual RP-TNC antenna connectors for 2.4-GHz radios	Antenna connectors support a variety of Cisco 2.4-GHz antennas, providing range and coverage versatility.
Security	• Authentication • Security standards • Wi-Fi Protected Access (WPA) • WPA2 (802.11i) • Cisco Temporal Key Integrity Protocol (TKIP) • Cisco Message Integrity Check (MIC) • IEEE 802.11 WEP keys of 40 and 128 bits • 802.1X Extensible Authentication Protocol (EAP) types: ◦ EAP Flexible Authentication via Secure Tunneling (EAP FAST) ◦ Protected EAP Generic Token Card (PEAP GTC) ◦ PEAP Microsoft Challenge Authentication Protocol Version 2 (PEAP MSCHAP) ◦ EAP Transport Layer Security (EAP TLS) ◦ EAP Tunneled TLS (EAP TTLS) ◦ EAP Subscriber Identity Module (EAP SIM) ◦ Cisco LEAP • Encryption: ◦ Advanced Encryption Standard Counter Mode with Cipher Block Chaining Message Authentication Code Protocol (AES CCMP) encryption (WPA2) ◦ TKIP (WPA) ◦ Cisco TKIP ◦ WPA TKIP ◦ IEEE 802.11 WEP keys of 40 and 128 bits
Current support for 12 nonoverlapping channels, with potentially up to 23 channels	• Lower potential interference with neighboring access points simplifies deployment. • Fewer transmission errors delivers greater throughput.

Feature	Benefit
Rugged metal housing	Metal case and rugged features support deployment in factories, warehouses, the outdoors (NEMA enclosure required), and other industrial environments.
UL 2043 plenum rating and extended operating temperature	The access points support installation in environmental airspaces such as areas above suspended ceilings.
Multipurpose and lockable mounting bracket	The access points provide greater flexibility in installation options for site surveys, as well as theft deterrence.
Support for both local and inline power, including IEEE 802.1af PoE	- Power can be supplied using the Ethernet cable, eliminating the need for costly electrical power line runs to remotely installed access points. - The access points can be powered by IEEE 802.3af PoE, Cisco Inline Power switches, single-port power injectors, or local power.
Hardware-assisted AES encryption	The access points provide high security without performance degradation.

Product Specifications

Table 2 lists the product specifications for Cisco Aironet 1240G Series Access Points.

Table 2. Product Specifications for Cisco Aironet 1240G Series Access Points

Item	Specification
Part Number	- AIR-AP1242G-x-K9 - AIR-LAP1242G-x-K9 - Regulatory domains: (x = regulatory domain) - A = FCC - E = ETSI - P = Japan2 - Customers are responsible for verifying approval for use in their individual countries. To verify approval and to identify the regulatory domain that corresponds to a particular country, please visit: http://www.cisco.com/go/aironet/compliance - Not all regulatory domains have been approved. As they are approved, the part numbers will be available on the Global Price List.
Data rates supported	802.11g: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, and 54 Mbps
Network standard	IEEE 802.11b and 802.11g
Uplink	Autosensing 802.3 10 and 100BASE-T Ethernet
Frequency band and operating channels	Americas (FCC) 2.412 to 2.462 GHz; 11 channels ETSI 2.412 to 2.472 GHz; 13 channels Japan2 2.412 to 2.472 GHz; 13 channels Orthogonal Frequency Division Multiplexing (OFDM) 2.412 to 2.484 GHz; 14 channels CCK
Nonoverlapping channels	802.11b/g: 3 channels
Receive sensitivity (typical)	802.11g 1 Mbps: -96 dBm 2 Mbps: -93 dBm 5.5 Mbps: -91 dBm 6 Mbps: -91 dBm 9 Mbps: -85 dBm 11 Mbps: -88 dBm 12 Mbps: -83 dBm 18 Mbps: -81 dBm 24 Mbps: -78 dBm 36 Mbps: -74 dBm 48 Mbps: -73 dBm 54 Mbps: -73 dBm

Item	Specification	
Available transmit power settings (Maximum power setting varies by channel and according to individual country regulations.)	802.11g	
	CCK: • 20 dBm (100 mW) • 17 dBm (50 mW) • 14 dBm (25 mW) • 11 dBm (12 mW) • 8 dBm (6 mW) • 5 dBm (3 mW) • 2 dBm (2 mW)	OFDM • 17 dBm (50 mW) • 14 dBm (25 mW) • 11 dBm (12 mW) • 8 dBm (6 mW) • 5 dBm (3 mW) • 2 dBm (2 mW) • -1 dBm (1 mW)
Range (typical)	Indoor (distance across open office environment):	Outdoor:
	802.11g: • 105 ft (32m) at 54 Mbps • 180 ft (55m) at 48 Mbps • 260 ft (79m) at 36 Mbps • 285 ft (87m) at 24 Mbps • 330 ft (100m) at 18 Mbps • 355 ft (108m) at 12 Mbps • 365 ft (111m) at 11 Mbps • 380 ft (116m) at 9 Mbps • 410 ft (125m) at 6 Mbps • 425 ft (130m) at 5.5 Mbps • 445 ft (136m) at 2 Mbps • 460 ft (140m) at 1 Mbps	802.11g: • 120 ft (37m) at 54 Mbps • 350 ft (107m) at 48 Mbps • 550 ft (168m) at 36 Mbps • 650 ft (198m) at 24 Mbps • 750 ft (229m) at 18 Mbps • 800 ft (244m) at 12 Mbps • 820 ft (250m) at 11 Mbps • 875 ft (267m) at 9 Mbps • 900 ft (274m) at 6 Mbps • 910 ft (277m) at 5.5 Mbps • 940 ft (287m) at 2 Mbps • 950 ft (290m) at 1 Mbps
	Measured with 2.2-dBi dipole antenna for 2.4 GHz	
Compliance	Standards Safety • UL 60950-1 • CAN/CSA-C22.2 No. 60950-1 • UL 2043 • IEC 60950-1 • EN 60950-1 • NIST FIPS 140-2 level 2 validation Radio Approvals • FCC Part 15.247 • RSS-210 (Canada) • EN 300.328 (Europe) • ARIB-STD 33 (Japan) • ARIB-STD 66 (Japan) • AS/NZS 4268.2003 (Australia and New Zealand) • EMI and susceptibility (Class B) • FCC Part 15.107 and 15.109 • ICES-003 (Canada) • VCCI (Japan) • EN 301.489-1 and -17 (Europe) • EN 60601-1-2 EMC requirements for the Medical Directive 93/42/EEC Security • 802.11i, WPA2, WPA • 802.1X • AES, TKIP Other • IEEE 802.11g and IEEE 802.11a • FCC Bulletin OET-65C • RSS-102	

Item	Specification
Antenna connectors	2.4 GHz - Dual RP-TNC connectors
Status LEDs	- Status LED indicates operating state, association status, error or warning condition, boot sequence, and maintenance status. - Ethernet LED indicates status of activity over the Ethernet. - Radio LED indicates status of activity over the radio.
Dimensions (H x W x D)	1.1 x 6.6 x 8.5 in. (2.79 x 16.76 x 21.59 cm)
Weight	2.0 lb (0.9 kg)
Environmental	- Nonoperating (storage) temperature: -40 to 185°F (-40 to 85°C) - Operating temperature: -4 to 131°F (-20 to 55°C) - Operating humidity: 10 to 90 percent (noncondensing)
System memory	32 MB RAM 16 MB flash memory
Input power requirements	100 to 240 VAC; 50 to 60 Hz (power supply) 36 to 57 VDC (device)
Powering options	- Local power 802.3 AF switches - Cisco higher-power switches capable of supporting 13W or greater - Cisco Aironet power injectors (PWRINJ3 and PWRINJ-FIB) - Third-party PoE devices (must meet input power and power draw requirements)
Power draw	12.95W maximum Note: 12.95W is the maximum power required at the powered device. If the access point is being used in a PoE configuration, the power drawn from the power sourcing equipment will be higher by some amount dependent on the length of the interconnecting cable. This additional power can be as high as 2.45W, bringing the total system power draw (access point and cabling) to 15.4W.
Warranty	90 days
Wi-Fi certification	

System Requirements

Table 3 lists the system requirements for Cisco Aironet 1240G Series Access Points.

Table 3. System Requirements for Cisco Aironet 1240G Series Access Points

Access Method	Description
Browser	Using the Web browser management GUI requires a computer running Internet Explorer Version 6.0 or later, or Netscape Navigator Version 7.0 or later.
PoE	Power sourcing equipment is compliant with Cisco Inline Power or IEEE 802.3af, and provides at least 12.94W at 48 VDC.

To place an order, visit the Cisco Ordering Website at:

Table 4 lists the product part numbers for Cisco Aironet 1240G Series Access Points.

Table 4. Product Part Numbers for Cisco Aironet 1240G Series Access Points

Part Number	Description
AIR-AP1242G-A-K9	802.11g non-modular Cisco IOS access point; RP-TNC; FCC configuration
AIR-AP1242G-E-K9	802.11g non-modular Cisco IOS access point; RP-TNC; ETSI configuration
AIR-AP1242G-P-K9	802.11g non-modular Cisco IOS access point; RP-TNC; Japan2 configuration
AIR-LAP1242G-A-K9	802.11g non-modular LWAPP access point; RP-TNC; FCC configuration
AIR-LAP1242G-E-K9	802.11g non-modular LWAPP access point; RP-TNC; ETSI configuration
AIR-LAP1242G-P-K9	802.11g non-modular LWAPP access point; RP-TNC; Japan2 configuration

Cisco offers a wide range of services programs to accelerate customer success. These innovative programs are delivered through a unique combination of people, processes, tools, and partners, resulting in high levels of customer satisfaction. Cisco services help you protect your network investment, optimize network operations, and prepare your network for new applications to extend network intelligence and the power of your business. For more information about Cisco services, visit [Cisco Technical Support Services](#) or [Cisco Advanced Services](#).

For more information about the Cisco Aironet 1240G Series, visit <http://www.cisco.com/go/wireless> or contact your local Cisco account representative.



Americas Headquarters:
Cinco Systems, Inc.
170 West Beaman Drive
San Jose, CA 95134-1700
USA
www.cinco.com
Tel: 408.538-4500
Fax: 408.538-4500
Fax: 408.537-0650

Asia Pacific Headquarters
Class Systems, Inc.
189 Robinson Road,
#28-01 Capital Tower
Singapore 068912
www.class.com
Tel: 65 6331 7773
Fax: 65 6331 7788

Europe Headquarters:
Cisco Systems International BV
Haarlembergpark
Haarlembergweg 13-18
1101 CH Amsterdam
The Netherlands
Email: corporate@ciscom.nl
Tel: +31 20 200 22022
Fax: +31 20 200 27100

Cisco has more than 200 offices worldwide. Addresses, phone numbers and fax numbers are listed on the Cisco Website at www.cisco.com/go/offices.

[illegible]

All other trademarks mentioned in this document or the labels are the property of their respective owners. The use of the word "feature" does not imply a relationship, additionally between iCase and any other company. 0720107

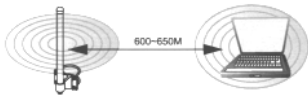
Appendix J

Antenna Specifications

• Specification

Frequency Range	2.4~2.5GHz
Impedance	50 Ω
Gain (Exclude Cable Loss)	8dB@ 2.45GHz
Storage Temp.	-20°C→+80°C
Operating Temp.	-10°C→+60°C
HPBW/H-plane	360°
HPBW/E-plane	15°
Dimensions LxWxH	623x80x107mm
Warranty	One Year
Connector	N-Jack

• Extended range



Extended wireless network coverage : 600-650 M



FOR REFERENCE
Ver. 1.00 2008.08.13

Range Extender Antenna for AP/Router With Replaceable Antenna

Quick Installation Guide
8dBi Omni



- Package Contents
Holder, Hose Clamp, Screw nuts, Screws,
Plastic fixings, Washer, Sticker
- Free Gift Waterproof Tape

8dBi Omni

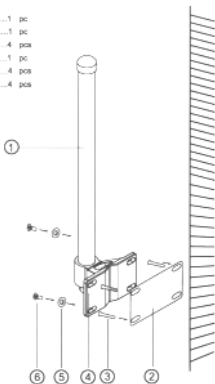
Quick Installation Guide

>>>

Two mounting methods are available for 8dBi Omni Antenna

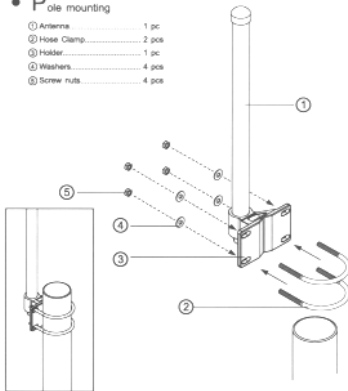
• Wall mounting

- ① Antenna..... 1 pc
- ② Sticker..... 1 pc
- ③ Plastic Fringe..... 4 pcs
- ④ Holder..... 1 pc
- ⑤ Washers..... 4 pcs
- ⑥ Screws..... 4 pcs



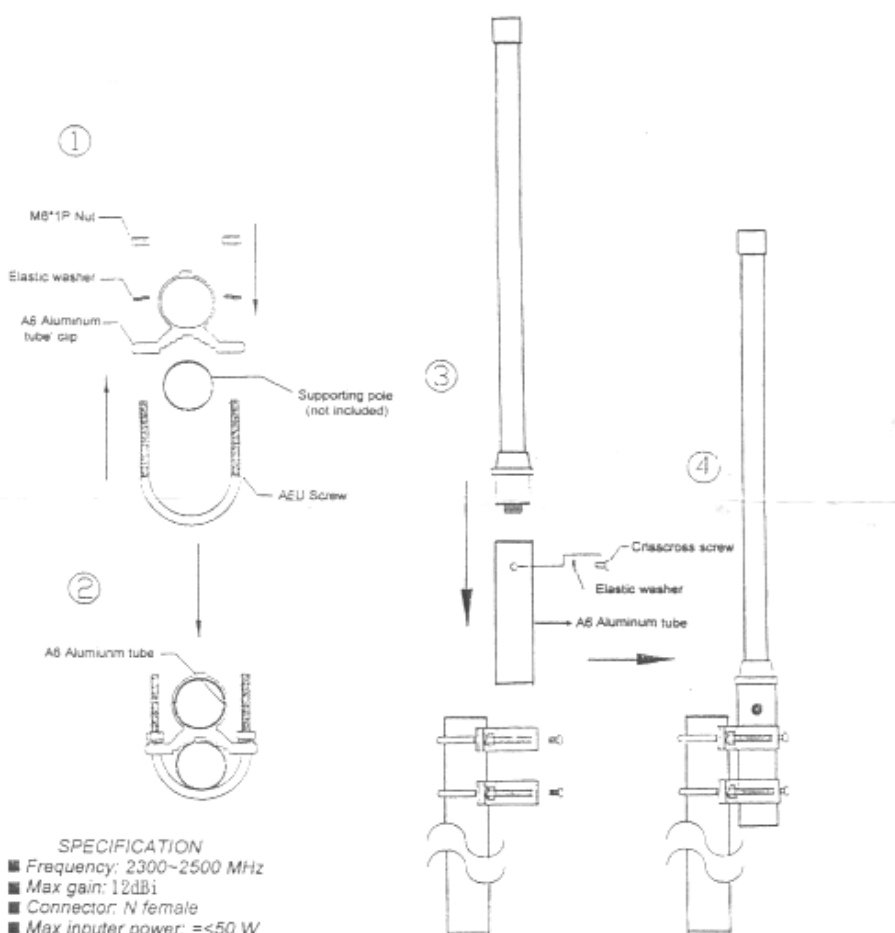
• Pole mounting

- ① Antenna..... 1 pc
- ② Hose Clamp..... 2 pcs
- ③ Holder..... 1 pc
- ④ Washers..... 4 pcs
- ⑤ Screw nuts..... 4 pcs



2.4GHz RF HI-GAIN DIPOLE ANTENNA

ITEM NO. : OA-2450-12



SPECIFICATION

- Frequency: 2300~2500 MHz
- Max gain: 12dBi
- Connector: N female
- Max input power: ≤50 W
- Size: H1420mm
- Weight: 590g
- For Image/ Data/ Voice communications and Wireless LAN system

Upphovsrätt

Detta dokument hålls tillgängligt på Internet — eller dess framtida ersättare — under 25 år från publiceringsdatum under förutsättning att inga extraordinära omständigheter uppstår.

Tillgång till dokumentet innebär tillstånd för var och en att läsa, ladda ner, skriva ut enstaka kopior för enskilt bruk och att använda det oförändrat för icke-kommersiell forskning och för undervisning. Överföring av upphovsrätten vid en senare tidpunkt kan inte upphäva detta tillstånd. All annan användning av dokumentet kräver upphovsmannens medgivande. För att garantera äktheten, säkerheten och tillgängligheten finns det lösningar av teknisk och administrativ art.

Upphovsmannens ideella rätt innefattar rätt att bli nämnd som upphovsman i den omfattning som god sed kräver vid användning av dokumentet på ovan beskrivna sätt samt skydd mot att dokumentet ändras eller presenteras i sådan form eller i sådant sammanhang som är kränkande för upphovsmannens litterära eller konstnärliga anseende eller egenart.

För ytterligare information om Linköping University Electronic Press se förlagets hemsida <http://www.ep.liu.se/>

Copyright

The publishers will keep this document online on the Internet — or its possible replacement — for a period of 25 years from the date of publication barring exceptional circumstances.

The online availability of the document implies a permanent permission for anyone to read, to download, to print out single copies for his/her own use and to use it unchanged for any non-commercial research and educational purpose. Subsequent transfers of copyright cannot revoke this permission. All other uses of the document are conditional on the consent of the copyright owner. The publisher has taken technical and administrative measures to assure authenticity, security and accessibility.

According to intellectual property law the author has the right to be mentioned when his/her work is accessed as described above and to be protected against infringement.

For additional information about the Linköping University Electronic Press and its procedures for publication and for assurance of document integrity, please refer to its www home page: <http://www.ep.liu.se/>